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THE INSTITUTE OF PETROLEUM.

An Ordinary General Meeting of the Institute of Petroleum was held at Manson House, 26 Portland Place, London, W.1, on Wednesday, February 9, 1949, T. Dewhurst (Past-President) in the Chair.

The Minutes of the preceding Ordinary General Meeting, held on January 12, 1949, were read, confirmed, and signed.

The Secretary (D. A. Hough) announced the elections to membership since the previous Ordinary General Meeting.

The Chairman: The business of this meeting is the presentation and discussion of a paper entitled "Production from Condensate Reservoirs," by L. C. Stevens (Fellow) and B. P. Boots.

The paper is especially welcome because it is the first to be presented to the Institute on this subject. Although the subject is comparatively new, it is already of considerable importance, and its importance will increase rapidly as a result of the ever deeper drilling which is being carried on in all parts of the world. Even to-day condensate and natural-gas liquids constitute a considerable part of the total liquid hydrocarbon reserves of the United States.

As will become apparent to you, the authors are masters of their subject; unfortunately Mr Boots is not able to be with us this evening. But I am delighted, on behalf of the Institute, to welcome Mr Stevens, who will present the paper. He has been a Fellow of the Institute ever since the Fellowship was founded.

The following paper was then read:—

PRODUCTION FROM CONDENSATE RESERVOIRS.

By L. C. Stevens (Fellow) and B. P. Boots.

Summary.

Part I deals with the phase behaviour of condensate reservoir fluids and explains the significance of "retrograde condensation." Tables showing the composition in mol percentage of some typical reservoir fluids are given, and the method of estimating liquid hydrocarbon recoveries is indicated.

Part II deals with the practical aspects of "gas cycling." The location of the various cycling fields in the U.S.A., together with important field and plant details, are shown by means of a map and a tabulation. The various physical conditions under which distillate occurs in natural reservoirs are discussed and classified. The method of sampling and analysis is indicated.

Some practical operating problems are illustrated by reference to experience in a specific field (Sheridan, Texas); in particular, corrosion, model studies, injection patterns, and the effect of permeability variations.

A brief outline of "Condensate recovery processes" and "Gas hydrates" follows, and the paper concludes with a section on the "Economics of gas cycling." A selected bibliography of American papers on this subject is appended.

Introduction.

The phase conditions in which petroleum hydrocarbons may be found in a natural reservoir when it is first tapped, fall into three classes :—

(*a*) entirely in the liquid phase, all the gas being in solution in the oil;

(*b*) as a two-phase system—that is, an oil column and an original gas cap;

(*c*) entirely in the gaseous phase—the term " gaseous phase " being used in this instance to include fluid above the critical state; such reservoirs are usually referred to as " condensate reservoirs " or " distillate fields " because of the nature of the crude oil produced.

It is the physical phenomena peculiar to this latter type of reservoir and the special technique required for their efficient production which is to be the subject of this paper.

Part I deals with the theoretical aspect of the matter, namely, the phase behaviour of the fluid contents of a condensate reservoir under varying conditions of pressure and temperature. This leads to an explanation of the phenomenon known as " retrograde condensation "; which is the phenomenon responsible for the remarkable features of " condensate reservoirs." It was several years after their discovery before the physical laws governing them became apparent to petroleum operators. In consequence, considerable losses of valuable petroleum fractions took place in the early fields of this type; among which can be named Turner Valley, Alberta, discovered in 1924, Kettleman Hills North Dome, California, and Big Lake, Texas, both discovered in 1928.

Although " retrograde condensation " had first been recognized as a physical phenomenon by Cailletet [1] in 1880, it was not explained until some years later, chief credit for the experimental work in this connexion going to Kuenen [2] of Leyden (Holland), who first used the term in 1892. Its significance in petroleum reservoirs was first brought to the attention of the industry by Lacey [3] in 1932.

The special technique frequently applied in modern practice to produce such reservoirs is commonly referred to as " gas cycling." The practical angles of " cycling " form the subject of the second part of the paper.

PART I. THE PHASE BEHAVIOUR OF CONDENSATE RESERVOIR FLUIDS.

Composition of Condensate Reservoir Fluids.

The salient feature of the typical condensate (or distillate) field is the production of a light straw-coloured oil of low specific gravity, together with large quantities of gas; the gas–oil ratios usually exceed 10,000 cu. ft./brl, ranging up to 50,000 cu. ft./brl and more. In such cases it is common practice to express the ratio of liquid to gas produced in the inverse sense to that used in normal field practice, that is, in gallons per thousand cu. ft. (G.P.M.) or barrels per million cu. ft. of separator gas referred to a standard base, say, 14·7 p.s.i.a. and 60° F. The abbreviation G.P.M. is usually used to denote U.S. gallons of butanes plus per thousand cu. ft. which practice will be followed in this paper (1 G.P.M. = 23·6 brl/million cu. ft.).

However, since the actual ratio of liquid to gas produced depends on the pressure and temperature under which the surface separation takes place, it is preferable in any physical study to compare the hydrocarbon mixtures occurring in condensate fields on the basis of the concentration of the various hydrocarbons of which the particular reservoir fluid is composed.

Table I gives the composition of some typical condensate reservoir fluids, and Table II compares the analysis of a typical condensate reservoir fluid

TABLE I.

Composition of Some Typical Condensate Reservoir Fluids.

All figures in mol per cent.

	A Typical lean gas	B Typical rich gas	C (Table IV [4]).	D (Table I [5]).	La Pice District, Louisiana.	Colorado "H" sand Santa Ana, Eastern Ven.[6]
Methane	93·405	80·851	94·11	89·50	93·88	69·21
Ethane	3·008	7·449	2·67	4·56	3·57	9·03
Propane	1·024	3·454	0·89	1·91	1·05	6·65
*iso*Butane	0·803	2·615	0·21	0·47	0·57	1·55
n-Butane			0·34	0·49		2·10
*iso*Pentane	0·345	5·631	0·20	0·27	—	0·46
n-Pentane			0·10	0·21	0·93	
Hexanes plus	1·415		1·38	2·38		6·22
(CO_2 + N)	—	—	—	0·21	—	4·78
Total butanes plus, brl/million cu. ft.	24·32	79·88	—	41·9	17·10	74
Total pentanes plus, brl/million cu. ft.	18·22	59·80	—	32·7	12·84	—

TABLE II.

Compositions of a Retrograde Gas and a Crude-Oil–Gas Mixture from O. F. Thornton.[7]

All figures in mol per cent.

	Retrograde gas.			Crude-oil–gas mixture.		
	Gas.	Condensate.	Reservoir fluid.	Gas.	Oil.	Reservoir fluid.
Methane	91·32	—	87·07	92·80	—	57·83
Ethane	4·43	—	4·39	3·79	—	2·75
Propane	2·12	1·41	2·29	1·97	1·61	1·93
Butanes	1·36	5·71	1·74	0·96	2·24	1·60
Pentanes	0·42	8·11	0·83	0·28	2·45	1·15
Hexanes	0·15	10·46	0·60	0·13	3·47	1·59
Heptanes and heavier	0·20	74·31	3·08	0·07	90·23	33·15
Total	100·00	100·00	100·00	100·00	100·00	100·00
A.P.I. gravity of heptanes and heavier, deg.			51·2			36·9
Molecular weight of heptanes and heavier			157			226

to that of a normal crude-oil reservoir. The method of sampling and analysis will be given in Part II. In most instances the fractional analysis is not carried beyond hexanes (or even pentanes).

The heavy fraction, designated as heptanes plus (or hexanes plus), consists of a large number of compounds which will show wide variations in composition between different fields. It may even contain compounds with boiling points above 600° F (in contrast to the boiling point of heptane at 209·1° F). In general, in condensate reservoirs, the higher the original formation pressure and temperature, the greater can be the concentration of the high-boiling-point hydrocarbons and the higher can be the molecular weight of the heaviest component.

The analyses of the hydrocarbon mixtures occurring in condensate reservoirs show that methane is generally represented by a mol fraction of 75 per cent or more. The mol fraction of a particular component is defined as the number of mols of that component divided by the total number of mols of all substances present in the mixture. For example, a " pound " mol is defined as a quantity of material whose weight in pounds is equal to the molecular weight of the substance in question.

Theoretical Consideration of Binary Hydrocarbon Systems.

For the purpose of discussing the phase behaviour of any complex mixture, it is logical to try to simplify the picture by using the analogy of a binary system, taking the methane as one component and assuming that the other component represents all the other fractions combined. Binary systems with methane as one component and some other hydrocarbon (in the range of propane to *n*-decane) as the other, and also binary systems with ethane or propane as the lightest component (for instance, ethane and *n*-heptane) have been the subject of extensive laboratory investigation.[8–12]

For the purpose of explaining the mechanism of retrograde condensation it will be sufficient to consider the influence of three variables on the binary system, namely, pressure, temperature, and composition.

Pressure–Temperature Diagram.

Beginning with the influence of pressure and temperature on the individual components whose binary mixtures are to be studied, a temperature–pressure diagram can be drawn (Fig. 1) in which the vapour-pressure curve for component " A " is represented by the line *ab* and for component " B " by the line *de*. These curves separate the regions where each individual component exists as either a liquid or a gas. Only under the conditions of temperature and pressure represented by its vapour-pressure curve can the component exist as liquid and vapour in equilibrium. In accordance with Gibbs' phase rule, this is expressed as $n = c - p + 2$; or in words, if n (the number of degrees of freedom) is 1, and c (the number of components) is 1, p (the number of phases) will be 2. Going along the vapour-pressure curve of any one of the components in the direction of increasing pressure and temperature, the liquid phase is each time in equilibrium with a gaseous phase of greater density. The point where the two phases have equal density, and therefore the meniscus between the two disappears, is called *the critical point* and is defined for each substance by the critical temperature

and pressure. The vapour-pressure curve of any substance terminates at its critical point.

Turning to the case of any mixture of these same two components, then from Gibbs' equation, if c becomes 2 and p is 2, then n is 2 also, that is to say, two phases can co-exist with two degrees of freedom. Instead of being represented by a single line, the two-phase region for any particular mixture is represented on the diagram by an area which is bounded by a

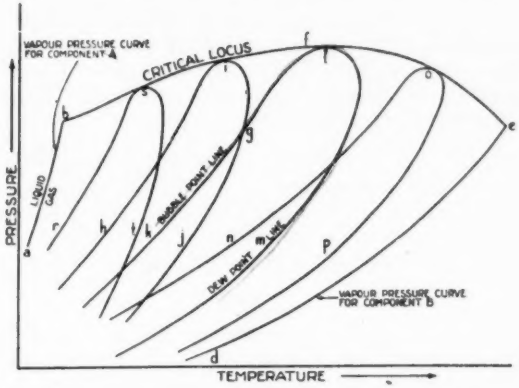


FIG. 1.

PRESSURE–TEMPERATURE DIAGRAM FOR A SERIES OF MIXTURES IN A TWO-COMPONENT SYSTEM.

loop-shaped curve such as those depicted in Fig. 1. Each mixture of different mol fractions of the same two components will have a different boundary curve. For any combination of temperature and pressure within the loop, representative for a particular mixture, two phases will exist, but outside of it only one phase will exist. Taking a typical loop such as *klm*, that part from the critical point (see below) towards the pressure axis is called the "*bubble-point line*"; under the conditions represented by this line the liquid phase still has the composition of the total mixture, but the gas phase is just appearing (or disappearing). That part of the loop from the critical point towards the temperature axis is called the "*dew-point line*" and represents the conditions of pressure and temperature under which the gas phase has a composition equal to that of the entire system and the liquid is just beginning to appear (or disappear) as a mist.

Critical Point for a Binary System.

At every point on the bubble-point line the gas phase in equilibrium with the liquid phase has a different composition. Going along that line in the direction of increasing temperature the composition of the gas phase gradually approaches that of the liquid phase (*i.e.*, that of the mixture in question), and at the critical point their compositions become the same. A similar reasoning for the dew-point line shows that dew-point line and bubble-point line must both end at the critical point.

It should be noted that, for the hydrocarbons occurring in natural re-

servoirs, the loop is of such a shape that the critical point for a binary mixture is not the highest temperature nor generally the highest pressure at which the two phases can co-exist. The highest temperature at which two phases can co-exist is frequently referred to as the " cricondentherm."

The locus of all the critical points of all possible mixtures of the two components (the line *bfe* on the diagram) represents the limits within which two phases for that binary system can co-exist; in other words any point outside the region on the pressure–temperature diagram bounded by that locus and the vapour-pressure curves of the two individual components represents conditions under which these two components or any mixture of them can exist only as a single phase. At any point within the two-phase region of a particular system either a single phase or two phases may exist dependent upon the composition of the particular mixture studied.

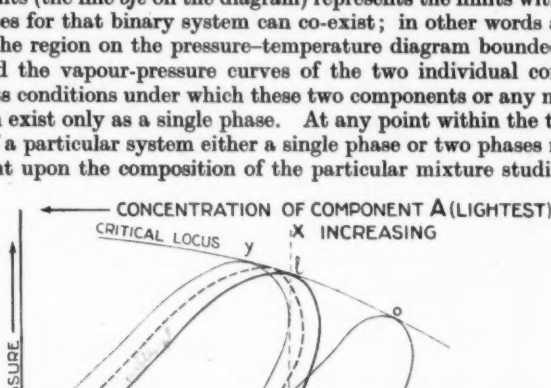


FIG. 2.

In a binary system of paraffin hydrocarbons only one bubble-point curve and one dew-point curve, each representative of a particular fixed composition, will intersect at any one point—for instance, point *g* in the diagram. For the two co-existing phases at this point, the composition of the gas phase will be equal to that of the mixture represented by the dew-point line, while the liquid phase has the composition represented by the bubble-point line. For all mixtures that have a greater concentration of the heavier component that than corresponding to the bubble-point line passing through the point under consideration, only a liquid phase can exist, *i.e.*, their two-phase boundary curve lies to the right in the diagram, for instance, loop *nop*, while for all mixtures in which the concentration of the lighter component is greater than that of the dew-point line, only a gas phase can exist, *i.e.*, their boundary curves lie entirely to the left of the point, for instance *rst*.

In an actual reservoir the original composition of the hydrocarbon mixture is fixed, and the temperature will not show much variation; therefore the most important change likely to occur on producing the reservoir is a drop in pressure. Temperature changes will of course take place between the reservoir and the tank.

To illustrate in greater detail conditions when an isothermal drop in

pressure occurs Fig. 2 has been prepared. It is in effect an enlargement of part of Fig. 1.

On the pressure–temperature diagram an isothermal change in pressure is represented by a vertical line. Starting at any point X above the two-phase region of the binary system under discussion and proceeding in the direction of decreasing pressures (vertically downwards on the diagram) the locus of critical points will be cut at some point, which is the critical point for a certain mixture, characterized, for instance, by a certain concentration (c_1) of the lightest component A and having a two-phase loop *klm*. All loops of mixtures with concentrations of component A less than c_1, *e.g.*, loop *nop*, will be cut by the vertical line somewhere on their bubble-point line and therefore will show the normal process of vaporization or ebullition with progressively decreasing pressure. The vertical pressure line will further be tangent to a particular loop (*xyz*), representative for a mixture having a concentration (c_2) of component A which is greater than c_1. All mixtures with concentrations of A greater than c_2 will, in line with what was discussed above, show no change of phase. Mixtures with concentration of A between c_1 and c_2 (*dotted line on the diagram*) will show " retrograde condensation " as their dew-point line will be cut twice by the vertical line.

Definition of Retrograde Condensation.

Sage and Lacey [13] define " retrograde condensation " (or vaporization) as a " *process in which a phase appears, increases in quantity, reaches a maximum, and then decreases again to complete disappearance, while one independent variable relating to the system as a whole changes continuously in one direction* (i.e., *progressively increases or decreases*) *and other variables, sufficient in number to fix the path of the system, are held constant.*" According to this definition the complete sequence of events from phase boundary to phase boundary is essential before the process can be classed as " retrograde." On the other hand, Brown and associates [14] have defined it as " *the formation of a more dense fluid phase by the isothermal decrease in pressure or the isobaric increase in temperature.*" This conception is perhaps not the classical one, but it has the merit of limiting the phenomena to that region where the somewhat abnormal event of condensation with decrease in pressure or increase in temperature takes place. It also defines more closely the region of interest from the petroleum-reservoir engineering standpoint. The region of retrograde behaviour according to this last definition is shown in detail for one particular two-component mixture in Fig. 3. The shaded area to the right of the critical point is the area in which retrograde condensation takes place on drop of pressure, and that to the left the area where retrograde vaporization is possible; this latter aspect of the phenomena has not the same degree of interest for field operations. As shown in Fig. 3, lines representing fixed ratios of liquid to gas can be drawn within the loop of any particular mixture; they follow the general trend of the loop and converge at the critical point. The vertical-pressure line will be tangent to one of these lines, *i.e.*, the one representing the maximum ratio of liquid to gas which will appear during the isothermal-pressure reduction. Condensation therefore takes place during isothermal-pressure decrease from the pressure at which the dew-point line is crossed until the vertical pressure drop line becomes tangent to a line of fixed liquid

to gas ratio. Upon further pressure decrease the quantity of liquid decreases, and the normal process of vaporization proceeds until all is in the gas phase once more.

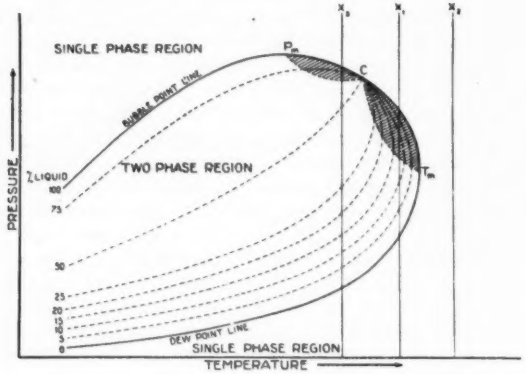


FIG. 3.

PHASE DIAGRAM ILLUSTRATING RETROGRADE PHENOMENA.

Pressure–Composition Diagram.

Another method of illustrating " retrograde condensation " of a binary system is by the pressure–composition diagram for a fixed temperature,

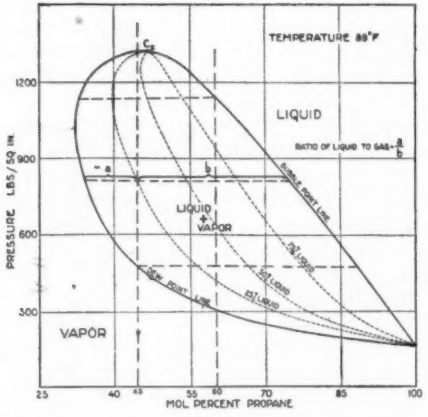


FIG. 4.

PRESSURE–COMPOSITION DIAGRAM FOR METHANE–PROPANE SYSTEM (*after Sage, Lacey, and Schaafsma*).

such as the methane–propane system shown in Fig. 4. In condensate fields the formation temperature is invariably above the critical temperature of the lighter component (methane), thus the two-phase region does

not extend from the vapour pressure of the heavy component to that of the lighter one, but forms a shorter loop, as the lighter component can only exist in a single gaseous phase. The compositions of the liquid and gas phases of a mixture represented by a point in the two-phase region are represented by the intersections of a horizontal line through that point with the bubble-point and dew-point line respectively. The ratio of the two phases is inversely proportional to the distances of that point to the points of intersection. In this diagram it is therefore a simple matter to construct lines of constant liquid–gas ratio. These lines all run from the vapour pressure of the heavier component to the point of tangency of a horizontal line to the loop enclosing the two-phase region. This point is the critical point for the mixture represented by it.

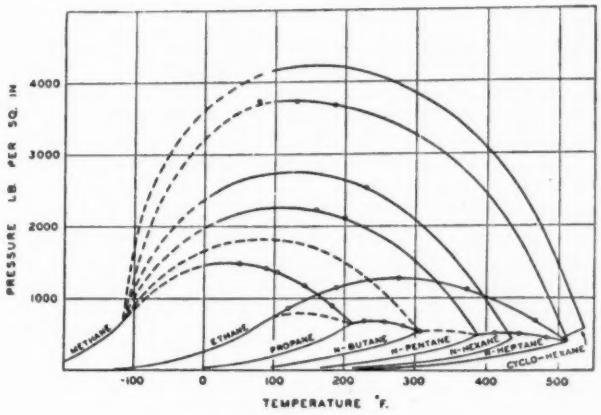


FIG. 5.

LOCI OF THE CRITICAL POINTS OF SEVERAL TWO-COMPONENT HYDROCARBON SYSTEMS.

In such a pressure–composition diagram a vertical line again represents an isothermal change in pressure. Such a line in crossing the loop between the critical point and the axis of the lighter component will cross the dew-point line twice and will be tangent to a line of fixed liquid–gas ratio, thus illustrating the phenomenon of retrograde condensation in a similar manner as was shown on the pressure–temperature diagram.

Application to Multi-component Systems.

As the simple rules which determine the composition of the phases for the binary systems discussed do not hold for multi-component systems, the pressure–composition diagram does not give an entirely complete picture for the study of petroleum reservoir fluids.

When the loci of critical states for binary systems of methane as one component and different hydrocarbons as the other are plotted on a pressure–temperature diagram (Fig. 5),[13] it can be seen that the maximum pressure at which two phases can exist increases with increasing difference between the molecular weights of the two components. In the same manner the

maximum pressure at which two phases can exist for multi-component mixtures, in which methane has a concentration of around 75 mol per cent,

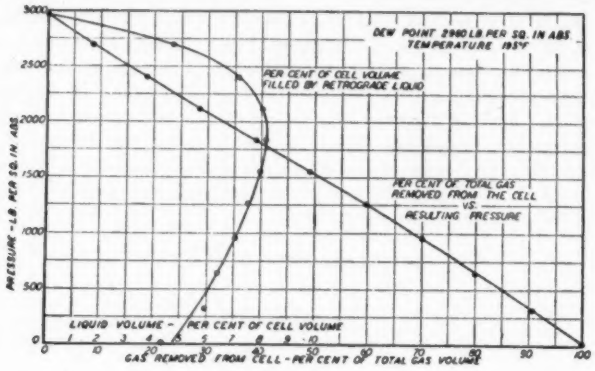

DEW POINT 2960 LB PER SQ. IN ABS
TEMPERATURE 195°F
PER CENT OF CELL VOLUME
FILLED BY RETROGRADE LIQUID
PER CENT OF TOTAL GAS
REMOVED FROM THE CELL
VS.
RESULTING PRESSURE
PRESSURE - LB PER SQ. IN ABS
LIQUID VOLUME - PER CENT OF CELL VOLUME
GAS REMOVED FROM CELL - PER CENT OF TOTAL GAS VOLUME

FIG. 6.

P.V.T. BEHAVIOUR OF TYPICAL CONDENSATE RESERVOIR FLUIDS.

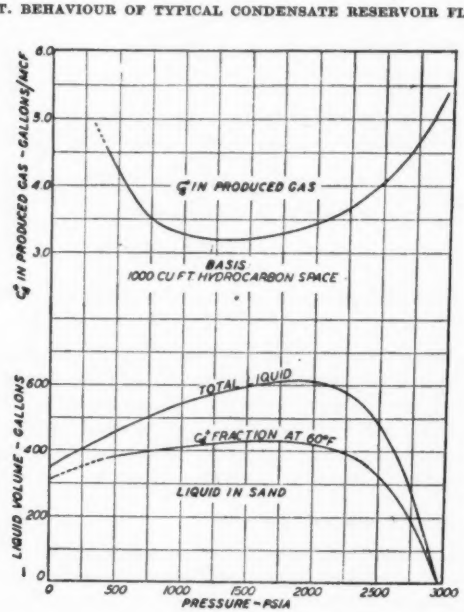


FIG. 7.

LIQUID–VOLUMES *vs* PRESSURE.

increases with greater differences between the components, that is methane and the heaviest fractions. However, because an actual reservoir fluid contains a range of intermediate hydrocarbons, the maximum pressure for

the existence of two phases is much less for fluids found in condensate fields than it would be for a binary system of methane and the heaviest fraction contained in the reservoir fluid. However, since the critical temperatures of the extreme components are so far apart, the boundary curve of the two-phase region for any particular natural-condensate fluid encloses a much greater area in which retrograde condensation can take place than would be expected by comparison with simple binary systems having similar maximum pressures for the co-existence of two phases. Thus in a multi-component system of the oilfield type, the phenomenon has an added significance.

Evaluation of Condensate Recovery; Liquid Volume–Pressure Diagram.

As the temperature in the reservoir may be assumed to remain constant a diagram showing liquid–gas ratio or liquid-volume against pressure at the particular reservoir-temperature has been found of practical value. Diagrams of this type can be determined in the laboratory by withdrawing in steps a part of the gas phase from a pressure cell containing a sample of the reservoir fluid. A typical result is illustrated in Figs. 6 and 7 taken from a paper by Standing, Lindblad, and Parsons [15]; Fig. 6 gives the data as obtained from the pressure cell and Fig. 7 shows the data converted to field terms. It should be noted that these diagrams represent the behaviour of hydrocarbon mixtures of continually changing composition and therefore provide the best indication of the probable production behaviour of a condensate reservoir producing without benefit of water drive or cycling operations.

Curves showing the total volume of condensed liquid in gallons per thousand cu. ft. of effective pore space against pressure are, however, somewhat misleading if used to assess the loss of distillate due to failure to cycle the field; since these volumes are appreciably larger than the actual volumes it would have been possible to recover at the surface, due to the volume of light hydrocarbons in solution in the total liquid condensed under the high reservoir pressures. For a complete investigation of the probable loss, it is therefore necessary to determine the volume of the various components in the condensed liquid or, since it is difficult and costly to make a complete analysis in every case, at least to determine the volume of *n*-butane and heavier. This result is given in the lower curve in Fig. 7.

During experiments to determine the above information, measurements can also be made of the volume of the butanes plus fraction contained in the gas withdrawn from the cell at each step; this information is shown in the upper curve of Fig. 7. When combined with the cumulative gas withdrawn (from the gas-volume curve, Fig. 6), a graph can be constructed showing, for instance, the cumulative recovery per thousand cu. ft. of effective pore space against reservoir pressure under different methods of exploitation. Due allowance must be made for connate water in estimating the effective pore space. The above data can be used to make a reasonable prediction of the performance of a condensate reservoir for evaluation purposes. A typical evaluation report of this type has been published by Horner and Trostel [16] for the " Benton Field Unit," Louisiana.

PART II. PRACTICAL ASPECTS OF PRODUCTION FROM CONDENSATE RESERVOIRS.

Introduction.

The first instance where the phenomenon of retrograde condensation was taken into account in the exploitation of a field was the Agua Dulce field, South Texas, where the first cycling scheme for a condensate reservoir was completed in 1937.

In the ten years since this date, some fifty cycling plants have commenced operations in the U.S.A. The location of most of the fields being cycled is shown on the map (Fig. 8), and some relevant details of these fields and

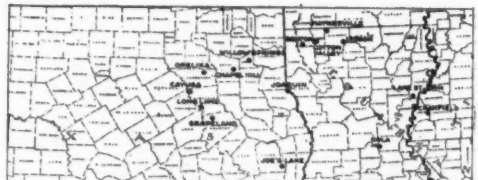


Fig. 8.

LOCATION OF CYCLING FIELDS IN TEXAS AND LOUISIANA.

plants are given in Table III. By far the greatest number of these is located along the fringe of the Gulf of Mexico in South Texas and Southern Louisiana, stretching from the Rio Grande to the Mississippi. There are some fields to the North of Houston in the Tyler Basin (East Texas), a few in Northern Louisiana, one in Mississippi, and two in California (Paloma and Coles Levee).

The geological age of the productive levels ranges from Miocene in South Louisiana, Oligocene and Eocene in South Texas, Lower Cretaceous in the Tyler Basin, to Jurassic in North Louisiana. They are generally flat structures with little or no faulting. Water drive of any appreciable magnitude is not known to occur in any of these fields.

At present there do not appear to be any condensate cycling operations outside the U.S.A., although the presence of condensate reservoirs is already known, for instance in the Eastern Venezuelan basin and in Serang Djaja in Sumatra. It may be anticipated that, with the advent of deeper

drilling, increasing numbers of condensate reservoirs will be discovered in areas outside the U.S.A., and cycling operations will undoubtedly be applied in a number of these.

To illustrate the relative importance of condensate reservoirs in the U.S.A. it has been estimated, in a combined report of the A.P.I. and A.G.A., that at December 31, 1946, the total liquid-hydrocarbon reserves of the country were divided as follows: crude oil 86·2 per cent; condensate and natural-gas liquids 13·8 per cent; an appreciable proportion of the latter will be recovered from cycling projects.

Gas-Condensate Reservoirs.

The classification used in the introduction for the different reservoir types needs some further qualification now that the mechanism of retrograde condensation has been explained. Referring to Fig. 3, it will be seen that the particular reservoir fluid, whose two-phase region is shown on the diagram, when above the critical temperature, can on isothermal reduction of reservoir pressure either pass, from a point such as X_1, through the retrograde region or can pass from a point such as X_2 to the right of the dew-point line. In the latter case the reservoir temperature is above the cricondentherm T_m, and no formation of liquid in the reservoir will occur. However, on cooling the produced gas at the surface, it is possible for conditions to cross into the two-phase region when a condensate will be formed in the separator. In contrast to the retrograde type, such fields will give a constant recovery of distillate with declining reservoir pressure, and pressure maintenance will be unnecessary to achieve maximum recovery. They are usually referred to as " wet gas " fields, a typical example being the gas fields in the Panhandle area of Texas. Where these conditions are found the reservoir fluids have normally a very low content of the heavier hydrocarbons, and the two-phase boundary forms a narrow loop just under the vapour-pressure curve of methane; thus normal reservoir temperatures can easily be higher than the cricondentherm.

When, however, reservoir temperature, in relation to the fluid composition, is such that, on pressure reduction, the retrograde region is entered, the heavier fractions of the reservoir fluid will be deposited in the reservoir and a progressive falling off in the recovery of liquid fractions in the surface separators will be observed. This has already been demonstrated by Figs. 6 and 7. To illustrate the magnitude of these losses in practice, the classic example of the La Blanca field is frequently quoted.[17] Fig. 9 shows the condensate recovery in brl/million cu. ft. and the gas–oil ratio plotted against reservoir pressure; the full line represents the field observations, the dotted part of the curve being calculated. The area below the curve indicates approximately the recovered portion, and that between the curve and the original content of 9 brl/cu. ft. the subsurface loss, in this case about 65 per cent. Subsurface loss due to failure to maintain pressure will vary according to a number of factors, the most important of which are the original reservoir pressures and the original composition of the gas. Generally, the richer the original gas the greater the loss.

It is, therefore, in reservoirs with fluids exhibiting retrograde condensation that the practice of cycling the dry gas back to the reservoir can be applied

TABLE III.

Data on Gas Cycling Operations in U.S. Fields.

Field.	County/ Parish.	Formation.	Depth, ft.	Area, acres.	Pressure, p.s.i.				Ratio	Condensate Recoveries.	Plant.			Remarks.
					Reservoir.	Wellhead.	Separator.	Injection	Inj/sep press	brl/ million cu. ft.	Type *	Capacity million cu. ft./ day	Compressor h.p.	
								South Texas.						
							—	—	—	6·8	PD	15,000	—	1st cycling operation 1937
							1,200	—	—	16·7	Abs	50,000	1,800	1st absorption plant 1939
Agua Dulce	Nueces	Frio (Olig.)	6,300/ 7,200	37,680	—		1,250	—	1·58	24	Abs	60,000	—	Wardner Plant
						2,060	1,550	—	1·67	—	Abs	140,000	4,000	Coastal Plant
							—	—	—	28·5	Abs	25,000	—	Lockart Plant
						1,840	1,320 / 1,400	2,580 / 3,380	1·95 / 2·42	—	Abs	100,000	2,400	Gulf Plains Plant
Alice Ben Bolt	Jim Wells	Frio Vicks	5,200/ 5,400	1,280	—	—	1,600	2,100	1·33	11·9	Abs	100,000	1,800	
Burnell	Karnes	Wilcox (Eoc.)	6,700	—	—	—	1,620	—	—	41	Abs	166,000	9,000	Under construction
Francitas	Jackson	Frio	7,200/ 7,900	1,560	—	—	1,635	3,100	1·89	36·4	Abs	60,000	1,600	
Goebel	Live Oak	Wilcox	7,000	—	—	—	—	3,200	—	20	PD	30,000	1,200	
La Gloria	Jim Wells/ Brooks	Frio Vicks	6,700	4,770	—	2,060/ 3,300	1,540	2,940	1·9	28·1	Abs	300,000	8,800	
La Rosa	Refugio	Frio	—	2,290	—	2,100	1,700	2,600	1·54	8·9	Abs	46,000	1,300	
Plymouth	San Patricio	Frio	5,500/ 6,200	3,750	—	—	—	—	—	37	—	48,000	—	
San Salvador	Hidalgo	Frio	7,300/ 8,700	1,800	—	—	1,800	3,800	2·11	8·4	Scrubber	30,000	1,200	
Seeligson	Jim Wells/ Kleberg	Frio	4,700/ 6,700	12,500	—	—	—	—	—	—	Abs	150,000	—	Under construction
Sejita	Duval	Jackson (Eoc.)	5,450/ 5,750	1,000	—	—	—	—	—	16·4	—	58,000	—	
Southland	Duval	Pettus (Eoc.)	5,290/ 5,330	780	—	—	—	—	—	11·5	—	12,000	—	
Stratton	Nueces/ Kleberg	Frio	6,320/ 6,600	11,000	—	1,760	1,250	3,090	2·47	28·5	PD + DC	65,000	3,000	1st big plant built in 1938
								North Texas.						
Bammel	Harris	Cockfield (Eoc.)	6,200	3,020	—	2,500	1,250	2,580	2·06	19·1	PD	50,000	2,400	
Blessing	Matagorda	Frio	8,200/	—	—	—	1,500	3,500	2·33	32·6	Abs	30,000	1,200	

Bammel	Harris	Cockfield (Eoc.)	6,200	3,020	—	2,500	1,250	2,580	2·06	19·1	PD	50,000	2,400	
Blessing	Matagorda	Frio	8,200/ 8,800	—	—	—	1,500	3,500	2·33	32·6	Abs	30,000	1,200	
Joe's lake	Tyler	Wilcox	7,650	1,300	—	—	—	—	—	29·6	—	10,000	—	
Joyce	Harris	Yegua (Eoc.)	6,900/ 7,400	3,760	—	—	1,300	2,900	2·23	12·6	Scrubber	30,000	1,300	
Richardson Katy	Waller	Cockfield	6,850/ 7,300	29,760	—	2,450	1,800	3,000	1·67	27·6	Abs	458,000	12,600	Largest plant to date
Lake Creek	Montgomery	Wilcox	9,200/ 11,800	5,700	4,300 5,370	—	1,030 1,470	4,260 5,150	4·14 3·50	156	Abs	42,500	4,800	5 prod. zones Richest field being cycled
North Houston	Harris	Yegua	7,170/ 7,440	2,270	—	—	1,625	3,400/ 2,800	2·08/ 1·72	31	Abs	60,000	1,200	
Old Ocean	Brazoria and Matagorda	Frio	9,660/ 10,960	11,500	1 { 4,472 orig. 3,210 now 2 { 5,200 orig. 4,980 now	— — — —	1,720	—	—	45·6 C_4 45·1 C_4	Abs	360,000	—	Total of 4 prod. zones being cycled
Pine Hurst	Montgomery	Wilcox	9,700/ 11,000	3,000	—	5,360	1,540	—	3·48	50·0	PD	19,000	1,600	Under construction
Seabreeze	Chambers	Frio	8,720	1,500	—	3,000	—	3,740	—	10	Scrubber	7,500	600	
Sheridan	Colorado	Wilcox	9,300/ 10,350	7,700	4,200	3,530	1,850	4,700	2·54	68	Abs	100,000	5,600	Built 1945
Willow Slough	Chambers	Frio	8,250/ 8,460	2,750	—	—	1,800	3,100/ 3,400	1·72	21·2	Scrubber	13,000	450	Processes gas from gas cap and oil-wells
						East Texas.								
Cayuga	Anderson	Woodbine (U. Cret.)	4,000	15,000	—	1,550	1,320	1,700	1·28	19·1	PD+DC	28,000 40,000	925 1,600	Both Tidewater plants Cooling to temp. −15°F
Chapel Hill	Smith	Paluxy (L. Cret.)	5,550	11,000	2,540	2,020	1,500	2,800	1·87	75·8	Abs	35,000	1,600	More than 100% gas returned
Grapeland	Houston	Woodbine	6,000	7,300	—	—	1,550 1,400 1,600	2,300 2,500 2,700	1·52 1·78 1·69	21·4 25 21·9	Abs Abs Abs	60,000 55,000 75,000	950 1,200 1,875	American Liberty Oil Co. Trinity–Lone Star Gas Co. Grapeland Oil Co.
Joaquin	Shelby	U. Glenrose (L. Cret.)	4,920	8,200	2,400	—	1,200	2,500	2·08	3·1	Scrubber	20,000	600	85% of gas returned
Long Lake	—	Woodbine	5,300	13,000	—	1,980 1,980 2,130 1,840	1,180 1,600 1,470 1,470	2,200 2,500 2,350 2,200	1·86 1·56 1·60 1·50	18·4 24 21·4 —	PD+DC PD+DC PD+DC PD+Abs	17,000 60,000 35,000 44,000	600 2,200 1,100 1,300	Trinity Gas Co. Tidewater plant, deep cooling to temp. −11° F Byrd Frost (*to* temp. −11° F
Opelika	Henderson	Rodessa (L. Cret.)	7,900	8,980	—	—	1,700	4,000	2·35	37·7	Abs	90,000	2,800	
Willow Springs	Gregg	Petit (L. Cret.)	7,300	4,600	—	—	1,700	3,000	—	—	—	—	—	

* P.D. Pressure drop with Joule–Thomson cooling effect. Abs. Absorption. D.C. Deep cooling.

TABLE III. *Data on Gas Cycling Operations in U.S. Fields.—(continued)*

Field.	County/ Parish.	Formation.	Depth, ft.	Area, acres.	Pressure, p.s.i.				Ratio	Condensate Recoveries.	Plant.			Remarks.
					Reservoir.	Well-head.	Separator.	Injection	Inj/sep press	brl/ million cu. ft.	Type •	Capacity million cu. ft.	Compressor h.p.	
							South Louisiana.							
Bateman Lake	St. Mary	M. Mio	9,600/ 11,000	3,514	4,810	4,120	2,060	—	—	26	PD + Abs	70,000	3,000	92% of gas return
Eola	Avoyelles	Cockfield / Wilcox	6,400/ 8,400	2,100	—	—	—	—	—	10·2	Abs	—	—	
Erath	Vermillion	M. Mio	7,000/ 11,600	3,150	4,070/ 6,480	—	1,910	4,780	2·50	38	Abs	200,000	13,000	89% of gas returned under water level
S. Jennings	Jeffers. Davies	L. Mio	8,600/ 10,900	1,845	—	—	1,900	1,900	—	25·5	Abs	55,000	1,200	
							North Louisiana.							
Benton	Bolssier	D Sand / Bodcaw (Jur.)	8,000	—	—	4,050	2,000	3,900	—	67	Abs	50,000	3,000	
Cotton Valley	Webster	D Sand / Bodcaw	7,900 and deeper	12,600 10,600	4,100 orig. 3,000 Mar. 46	1,980	1,500	2,900	1·96	72·2	Abs	150,000	7,200	90% of gas returned
Haynesville	Claiborne	L. Pettit	5,120	13,600	2,440 orig.	—	—	2,300	—	42	Abs	16,350	4,000	80% of gas returned
Lake St. John	Tensas	Tuscaloosa (Up. Cret.)	9,000	13,000	4,265 orig. 4,000 now	—	1,600	3,800	2·38	90	Abs	100,000	7,200	Condensate + black oil zone (area gas cap 6000 *acres*)
Lisbon	Claiborne	Travis Peak (Jur.)	8,400	5,200	—	—								
							Mississippi.							
Cranfield	Adams	Wilcox / Tuscaloosa	5,900 10,300	10,000	—	—	—	—	—	36	Abs	100,000	—	Started operations end 1947
							California.							
Coles Levee	Kern	Miocene	8,400/ 9,300	2,000	4,350	3,100	1,500	4,100	2·73	11·6	Abs	60,000	5,400	90% of gas returned
Paloma	Kern	Miocene	10,100	2,800	4,700	—	2,000	4,350	2·18	155	Abs	50,000	3,600	Very rich reservoir fluid

Note: The above data may be subject to errors as in some cases conflicting information has been found in publications, also changes may have taken place since date of publication.

• P.D. Pressure drop with Joule–Thomson cooling effect. Abs. Absorption. D.C. Deep cooling.

with advantage to avoid the deposition of the heavier fractions in the reservoir. The condensate which would otherwise be deposited generally amounts to only a relatively small fraction of the total pore space in the reservoir, which is then adsorbed on the sand grains making its subsequent recovery very difficult if not impossible.

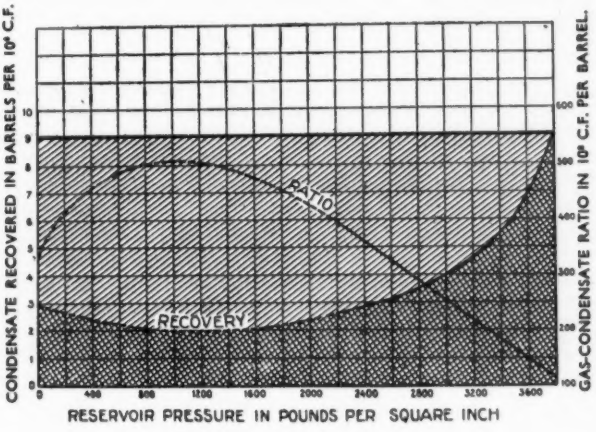

CONDENSATE RECOVERED IN BARRELS PER 10⁶ C.F.
GAS-CONDENSATE RATIO IN 10⁶ C.F. PER BARREL.
RATIO
RECOVERY
RESERVOIR PRESSURE IN POUNDS PER SQUARE INCH

FIG. 9.

LOSS OF CONDENSATE, LA BLANCA FIELD.

A third condition, of relatively rare occurrence, has been reported, where a condensate type of crude is produced but solution gas–oil ratios are of the order of 2000 to 5000 cu. ft./brl; this is much lower than normal for a distillate field and higher than normal for a crude-oil field. Laboratory experiments have shown that such fluids exist in the reservoir above the bubble point, at temperatures close to but below the critical, such as at point X_3 on the diagram. For the purpose of distinction these conditions have been referred to as the " reservoir liquid " type of condensate field. On pressure reduction gas will be evolved in the normal manner when the bubble-point line is crossed, but shrinkage when the fluid is brought to tank conditions will be of a very high order. Such reservoirs should preferably be produced by pressure-maintenance operations in order to avoid the liberation of large volumes of gas in the formation with the serious decrease of the relative permeability to the liquid phase causing high subsurface losses.

On moving farther away from the critical point (*i.e.*, to the left in the diagram) conditions pass into the region of a normal undersaturated crude reservoir classified as (*a*) in the introduction. Therefore in a strict sense, reservoirs classed under (*a*) and (*c*) should be regarded as the same type, namely " single-phase reservoirs," since physically a continual graduation from the one to the other is possible. However, in field practice, it is more convenient to make a distinction between the single-phase black-oil type of reservoir and the single-phase condensate type, the distinction, however,

being drawn according to the type of crude produced rather than the physical state prevailing in the reservoir. Furthermore, reservoir temperatures encountered, even at the greatest depths so far reached, would not be high enough to bring a single-phase crude-oil-type reservoir into the region of retrograde condensation.

Table IV gives a comparison of the salient characteristics of the three types of gas-condensate reservoir fluids and also, for contrast, a normal crude from a high-pressure Gulf Coast field.

TABLE IV.

Comparison of Typical Reservoir Conditions for Gas-condensate and a Crude-Oil–Gas Mixture from O. F. Thornton.[7]

	Gravity of liquid, A.P.I.°	Gas–liquid ratio, cu. ft./brl.	Reservoir conditions.		Retrograde dew point, p.s.i.	Bubble point, p.s.i.
			Temperature, ° F.	Pressure, p.s.i.		
Gas condensate :						
Wet gas . .	65	67,000	160	1,700	—	—
Retrograde gas	55	18,500	203	4,810	4,470	—
Reservoir liquid	58	2,700	203	4,700	—	3,855
Crude-oil–gas mixture :						
Gulf Coast .	38	900	211	4,750	—	4,600

Occurrence of Condensate in Conjunction with Oil—Class (b) Reservoirs.

Both " wet " and " retrograde " gas may occur as gas caps to crude-oil reservoirs. For the existence of a retrograde-gas cap conditions should lie within the two-phase boundary but above the point of maximum condensation of liquids for that particular mixture. The area in the pressure-temperature diagram in which this condition can occur, the shaded area to the right of the critical point in Fig. 3, is bounded by the dew-point line from the critical point to the cricondentherm as the upper boundary and a line drawn through the locus of the points of maximum liquid condensation as the lower boundary.

For reservoir conditions outside this area but within the two-phase boundary, two phases will exist, but on drop of pressure, normal vaporization takes place and such a reservoir would be regarded as a normal Class (*b*) reservoir.

Oil accumulations in two-phase fields may be of very small extent, occurring as a thin ring of liquid around the flanks (distillate rings), or they may occupy the major part of the total pore space (crude-oil column with gas cap).

Exploitation methods depend on the relative size, that is, the recoverable hydrocarbon content, of the oil zone and of the gas cap. Most frequently the oil zone predominates, and production from this is given preference. Condensate may be recovered from the solution gas and gas-cap gas in a gasoline-recovery plant. However, should it be considered desirable, due for instance to absence of water drive or as a storage measure, to adopt

pressure maintenance for maximum recovery from the oil zone, this can then be combined with cycling for maximum recovery of the gas-cap contents, should these lie in the retrograde region. This is being done, for instance, in the Lake St John field.

Sampling of Condensate Wells.

Accurate and reasonably frequent sampling of wells is necessary for initial reservoir appraisal, in order to decide whether to install cycling facilities, as well as for operational control during the productive life.

As soon as a distillate-type reservoir has been discovered, it is important to determine the characteristics of the reservoir fluid in relation to prevailing reservoir pressures and temperatures and its content of liquefiable products. Such determinations should be made at several points, especially in large reservoirs, because experience has shown that the fluid is frequently not homogeneous throughout the reservoir. It has proved impracticable to take bottom-hole samples of this type of reservoir fluid; thus, in order to obtain a representative sample, it is necessary to recombine, in their proper ratio, the gas and liquids withdrawn from a separator at the well-head. In order to minimize the risk that some condensation may occur in the formation immediately around the well bore, it is essential that, during sampling for reservoir appraisal, high drawdowns be avoided, and the wells should be produced at the minimum rate consistent with steady production; that is, without any liquid slugs forming in the tubing.

During exploitation, the output wells of a cycling project must be tested at regular intervals in order to determine the commencement and progress of the dry-gas invasion and finally the point at which they should be shut down on account of excessive dilution by dry gas. In fields which are not cycled, but where the gas is being stripped, it is generally also necessary to analyse the gas produced in order to decide the point at which the distillate content of individual wells in the system becomes too low for profitable extraction. For these purposes the wells are generally sampled while producing at their normal rates, although occasionally it is advisable to investigate to what extent the G.P.M. is affected by the rate of production.

Condensate wells are usually sampled by one of two methods—namely, *full-scale sampling*, in which the entire stream of gas and liquid produced is led through a separator, or *split-stream sampling*, in which only a part of the production is led through a small-scale separator.[18] In the latter method the sample is withdrawn from a small tube inserted in a vertical section of the flow line or the well tubing, and the velocity ratio of the fluid in the tube and flow line are adjusted in such a way that a representative sample is obtained. This method, therefore, requires checking for proper ratio of liquid to gas, against a full-scale separator operated under the same conditions. Producing wells are usually manifolded into common separators but with facilities for individual testing.

The determination of the total products in the fluid involves measurements such as the following :—

1. Ratio of the volumes of high-pressure gas and liquid as separated in the high-pressure trap.
2. Analysis of high-pressure gas; either for normal butanes plus

content by charcoal test or, for a complete analysis, a determination of mol fractions by low-temperature fractional distillation with a Podbielniak or similar apparatus.

3. Ratio of the volumes of low-pressure gas to remaining liquid volume, as obtained by flashing the liquid from the high-pressure trap to atmospheric conditions.

4. Analysis of the low-pressure gas, as in (2).

5. Shrinkage of the liquid from the high-pressure trap when flashed to atmospheric conditions.

6. Analysis of the liquid from the atmospheric trap; this can only be made by fractional distillation.

7. The gravities of the gas obtained from the high- and low-pressure trap, and of the liquid from the latter, are also determined.

As a complete analysis along the above lines is rather costly and time consuming, various simplifications are usually introduced for intermediate routine tests, until such time that a complete analysis is indicated. For most tests the G.P.M. in both the low- and high-pressure gas is determined by charcoal absorption, and the liquid obtained by flashing to atmospheric conditions is generally assumed to be all *n*-butane or heavier.

One of the chief objectives of testing is to determine the entry of dry gas in an output well; but since a change in content of butanes plus may be due to either retrograde condensation, or from dry-gas invasion or errors in the sampling or analysis, the actual situation may not be clear from a knowledge of the liquid contents. Lewis [19] from a study of test data mentions three indicators which are available for detection of dry-gas invasion: (1) the G.P.M. of the high-pressure separator gas; (2) the gravity of the high-pressure separator liquids; (3) the gravity of the high-pressure separator gas.

If the high-pressure trap used for testing is always operated at a fixed pressure, sufficiently far below the reservoir pressure, and at a fixed temperature, it has been found that the content of butanes plus in the high-pressure gas gives a reasonably good indication whether the fluid produced by the well is diluted with dry gas or not. As long as dry gas has not reached a well, it appears that the G.P.M. of the high-pressure gas remains constant, although the total G.P.M. content of the well fluid may gradually decrease, for instance, on account of condensation in the formation around the producing well (loading up). The gravity of the high-pressure separator gas and of the separator liquid also afford indications of dilution by dry gas, but they are generally less sensitive. The pressure selected for separation is normally close to the pressure of maximum condensation of the original formation fluid, which is usually in the range of 1000 to 1200 p.s.i.

Some Operational Problems in "Gas Cycling."

In order to illustrate the sort of problems likely to arise once "cycling" has been embarked upon, an outline of certain aspects of the operation of a typical cycling project in the "Sheridan" field will now be given.

The Sheridan field is located some 80 miles from Houston in Colorado County, Texas, and is operated by the Shell Oil Co. The development history of this field will serve to illustrate among others the following

practical points in connexion with the operation of a condensate field: (*a*) corrosion problems; (*b*) application of model studies; (*c*) injection pattern; (*d*) importance of permeability profile.

A subsurface contour map on the top of the "L" sand and a type section of the productive interval is shown in Fig. 10.

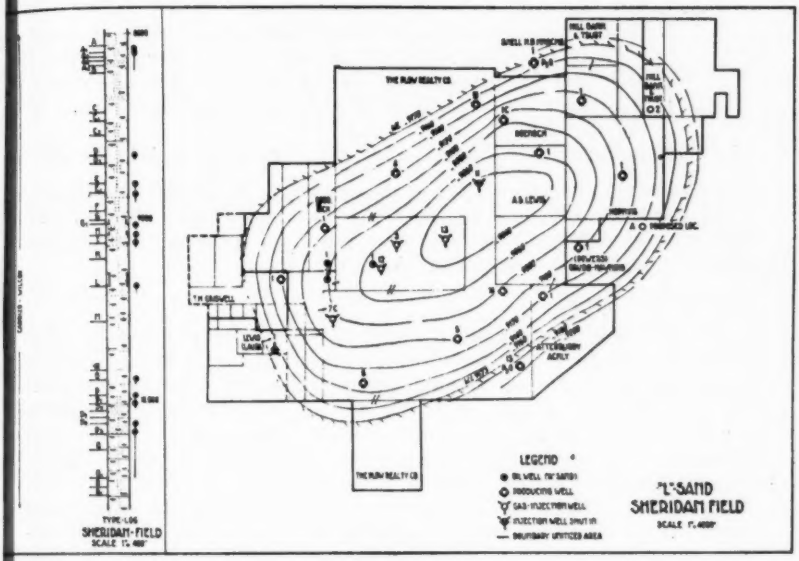


FIG. 10.

SHERIDAN STRUCTURE.

The discovery well was bottomed in the "A" sand (May 1940). This level had a thin oil column and a rather irregular sand development and was judged to be uneconomic after two more wells had been drilled. Deeper exploration (early 1941) exposed a series of condensate reservoirs of varying importance, the best of which were the "L" sand at 9300 ft. the P5–Q sand at 10,300 ft., and the "H" sand at 9100 ft. in that order.

Appraisal drilling was completed by November 1942 and the decision taken to recycle. Exploitation drilling ceased in August 1947, but recently it has been decided to drill two more wells. The plant was commenced in mid-1944 and started operation, not, however, at full capacity, in August 1945.

Steps had meanwhile been taken to pool as much as possible of the acreage; this has been successful with the exception of some 5 per cent shown on the map as falling outside the pooled area. Five companies, including Shell, form the pool, Shell owning a little more than 75 per cent. An additional subsidiary unit representing some 2 per cent of the total field area has recently been formed, and, if proved productive, will be added to the pool.

In order to economize on the number of wells, it was decided to drill all wells to the P5–Q zone, whereafter any zone can be opened as required by plugging and perforating.

A choice had to be made at the start between various systems of operation, namely :—

A. 1. Separate exploitation of a single zone, or
A. 2. Simultaneous but segregated exploitation of two zones by means of dually completed wells, segregation being necessary on account of differences in pressure and permeability between the zones.
B. 1. Injection wells centrally or axially located, with producing wells around the edges, or
B. 2. Injection wells located at one end; called " terminal injection."

Provisionally, and depending on experience to be gained, the decision was taken to try A-2 and B-1. Therefore, starting in August 1943, all wells were completed dually from the P5–Q zone and the L zone. Some physical details of the various zones follow later in the paper.

(a) *Corrosion Problems.*

The first problem encountered, after only a few months of operation, was serious trouble due to the corrosive action of the gas on the tubing and well-head connexions of output wells, especially those with the highest withdrawal rates. The magnitude of this problem is illustrated by the photographs of corroded and eroded well equipment (Fig. 11). Corrosion problems vary considerably from field to field. The corrosive agent is a highly concentrated and ionised solution of acids, mainly carbonic acid, which forms in the cooler parts of the system; corrosion due to sulphuretted hydrogen also occurs. Some reduction of the trouble was achieved by restricting the output of the larger producing wells to a maximum of 6 million cu. ft. per day each. Various inhibitors were tried, but the most effective way of combating corrosion in this particular case proved to be the use of special alloy steels. Several stainless-steel well-heads (13 per cent chromium) have now been fitted, and a trial with nickel-steel tubing is to be made. The cost of these special metals is two and a half to three times normal carbon steel.

Since it was feared that the casing might be attacked, with all the dangerous consequences attendant thereon, it was decided that, under these circumstances, a change to single-zone production was desirable. Other considerations, mentioned below, also prompted some alterations in the injection pattern about this time, and the opportunity was taken to convert the wells to single-zone operation.

Limited injection of corrosion inhibitors was commenced in March 1946, but was hampered by the system of dual-zone production. After single-zone production was adopted, provision was made for the injection of inhibitors into the casing whence it is blown back up the tubing and through the tree, field lines, and plant. Sodium dichromate, glycerol monooleate, sodium petronate, calcium naphthenate, Ionex 6F, sodium bicarbonate, Kontol 115 and 118 have all been used. Most have now been discarded, but Kontol 118 will afford 95 to 100 per cent protection under Sheridan conditions at a cost of about $1·40 per million cu. ft. of gas produced.

The following precautions are taken to watch corrosion: (1) inspection of well-head equipment on all producing wells every 3 to 4 months; (2) inspection of well equipment during workovers; (3) tubing caliper surveys; (4) inspection for weight loss of coupons installed in flow lines; (5) water-sample analyses for iron content.

(b) *Model Studies.*

In any cycling operation it is very important to anticipate the spread of the dry gas through the field, since maximum ultimate recovery of wet gas depends largely on locating the output wells so that the break-through of dry gas will be avoided for the longest possible time. It is therefore necessary to know the shape of the boundary between wet and dry gas at various stages in the cycling process and for various arrangements of wells and for various input and output rates, so that a scheme can be selected which will result in the maximum effective displacement of wet gas.

A mathematical solution of this problem can only be made for certain idealized arrangements of input and output wells and with only the simplest boundary conditions; it is impracticable for a field study on account of the labour involved. The practical approach is by means of models using the analogy which exists between Darcy's law for the flow of fluids in porous media and Ohm's law for the flow of electrical current in a conducting body.

Two model studies have been made since the initiation of cycling in the Sheridan field; an "electrolytic" model study in September 1946 and a "potentiometric" model study about a year later.

The electrical analogy is established by passing electrical currents proportional to the injection and extraction rates through a conducting body, simulating the areal shape of the reservoir, by means of electrodes located at points corresponding to the position of the wells in the field. Under these conditions the potential distribution in the conductor is analogous to the pressure distribution in the field, and the lines of electrical flux correspond to the flow lines. The conductor used is a solution of an electrolyte. The first method or "electrolytic model" is carried out in a field model, filled, for instance, with an agar gel containing an electrolyte such as zinc ammonium chloride. The transference of ions from the copper electrodes, representing the input wells, into the electrolyte, representing the field, gives a colour change, the edge of which corresponds to the front of the gas displacement in the field. It gives rapid results and involves little calculation, but accuracy is impaired by the diffusion of ions which results in loss of sharpness of the boundaries to be observed.

The following assumptions are necessary for the application of the electrolytic model:—

(1) horizontal permeability is uniform throughout the reservoir;

(2) relative permeability effects may be neglected;

(3) the viscosity difference between the driving and the driven fluid may be neglected;

(4) gravitational effects due to difference in density of the two fluids may be neglected;

(5) compressibility of the fluids may be neglected, that is pressure differentials are small compared to the absolute pressure.

With the exception of the permeability variations these assumptions are reasonably correct in cases of gas cycling.

Fig. 12 shows the results obtained by such a study made on the Sheridan field in 1946. The final flooding pattern is shown for six runs, together with the per cent of wet gas recovered and per cent of total gas cycled. The largest recovery is seen to be obtained with terminal injection as a result of sweeping the field outside the periphery of the longitudinal edge

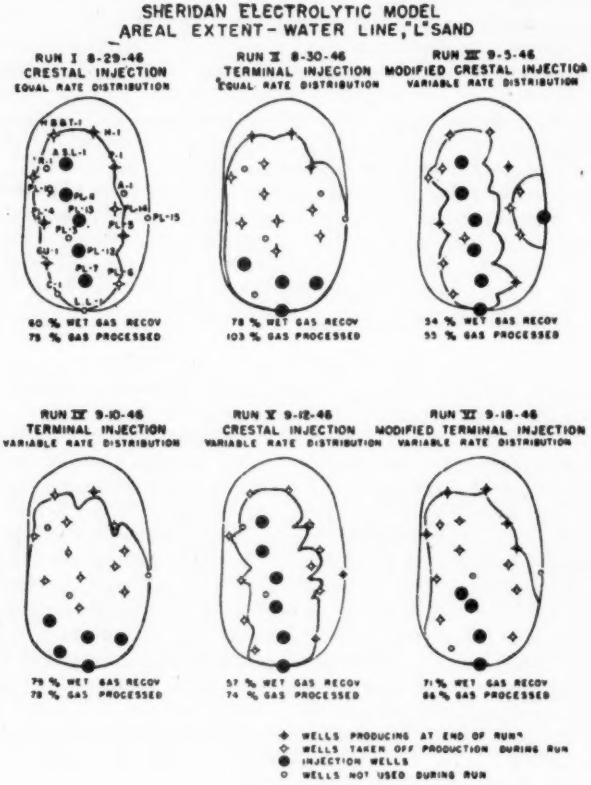


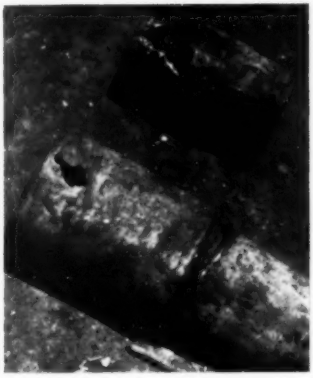
FIG. 12.

wells; an effect unobtainable with crestal injection because the dry-gas front nowhere reaches the periphery of the reservoir.

The second method known as the "potentiometric model," first described by Hurst and McCarty,[20] uses an aqueous electrolyte such as copper-sulphate solution in a pool, the depth of which may be uniform or which may be shaped to correspond to the calculated gas volume per unit of surface area in the reservoir, if this can be estimated within limits of reasonable accuracy. The boundary of the pool corresponds to the boundary of the field. Currents corresponding to injection and extraction rates are intro-

Top of tubing head flange, Plow No. 4, showing corrosion of ring groove and general pitting inside.

Top flange of master valve, Plow No. 4, showing heavy corrosion in bore.



Male end joint No. 21 and collar, Plow No. 14, showing how cut in middle engaged threads.

Tubing hangar, Plow No. 10, showing corrosion of threads and external upset.

FIG. 11.

EXAMPLES OF CORROSION IN SHERIDAN.

[*To face p.* 332.

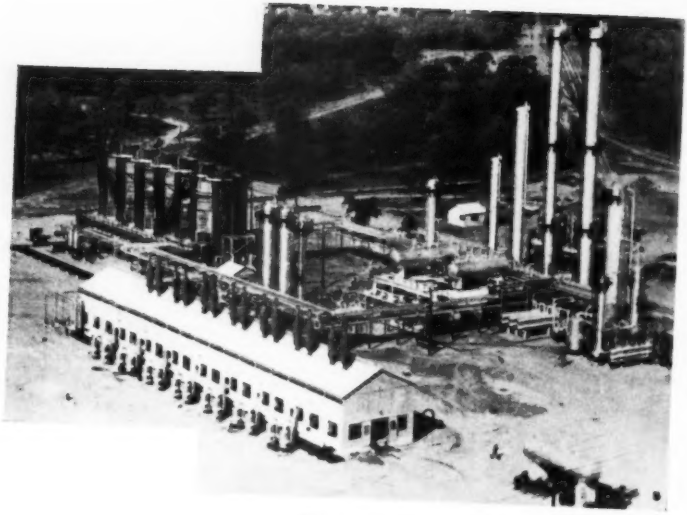


FIG. 14.

SHERIDAN CYCLING PLANT.

duced through metallic electrodes corresponding to the wells as in the electrolytic model.

The potential gradients along the stream lines are actually measured in the model, but the fluid fronts have to be calculated. The potential gradients along the stream lines are proportional to the velocity of the gas in the reservoir. The reciprocals of these gradients are therefore proportional to the transit time of the gas per unit distance, from which the transit time of the gas over an extended trajectory along a certain flow line can be calculated. The time-scale calibration can often be obtained, either from the volume of a flooded section of the reservoir surrounding a given injection well and the postulated injection rate into that well, or alternatively from reservoir-pressure data. For this purpose some knowledge of the actual performance of the reservoir under past producing conditions is necessary and, in the former case, particularly the time of first dilution in one or more producing wells.

In the application of the potentiometric model to a two-dimensional study of a reservoir, variations in permeability can be allowed for within limits; although in actual practice information on the actual permeability variations in the sand are often too scant to warrant adjustments in the model. It is this factor which causes the greatest discrepancies between model studies and actual experience in the field. The assumptions on viscosity and gravitational effects remain the same as for electrolytic models, but the compressibility factor can be allowed for in the formula for calculating transit times. The relative permeability effect could also be compensated for if it can be expressed as a function of pressure, but this is unnecessary when dealing with displacement of one gas by another.

(c) *Injection Pattern.*

As a result of certain idealized potentiometric model studies made by Lee [21] he concludes that

> "*Injection and extraction areas should be separated by as great a distance as conditions permit since in general the recovery prior to first break-through tends to vary as the square of this distance.*"

This would imply that for elongated shapes of productive limits the most efficient sweep can be obtained by placing the injection wells at one end of the longer axis, with a line of extraction wells at the opposite end of the field; usually called " terminal injection."

As mentioned before, a second study of the Sheridan field using the potentiometric method was carried out in October 1947.[22] Studies were made for three different arrangements of injection wells specifically adopting the terminal injection system, the total producing rates being practically constant in each case. By way of illustration the flooded area after the conclusion of the most favourable plan is shown in Fig. 13. The net result of these model studies was to show that there were definite advantages in a terminal injection pattern for the Sheridan field.

The original decision to locate the injection wells along the structural axis was taken because it gave the shortest distance between injection and producing wells and consequently smaller pressure loss in the tight Wilcox sands. Also the maximum thickness of the sand section was available for

injection. This reasoning originated from the belief that the Wilcox sand had a very low receptive capacity. Later, however, it was found that the intake capacity of the wells increased considerably, to as much as double their initial capacity, after a few months of injection. It has been assumed that this was probably due to the evaporation of connate water and/or the water from the mud which had penetrated the formation.

In the light of the information from the model studies, some of the injection wells to the east have been shut in, while in the west producing wells

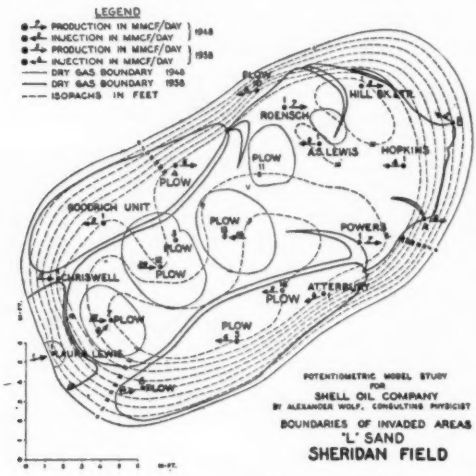


FIG. 13.

were converted to injection. As presently foreseen the total number of wells drilled for the entire project will be twenty-two, of which fifteen will be L sand producers, two of which on the eastern edge of the field or output end of the drive are still to be drilled; one a P5–Q producer (Plow 15) is closed in and six will be injection wells, four of which are in regular use and two are left as standbys. The two additional wells are required to maintain sufficient output capacity for maximum plant operation and to obtain maximum cycling efficiency. All wells are completed so that the P5–Q sand can be reopened when required. Two of the wells lie outside the pooled area, one Shell Knoché was too poor a producer to validate the acreage for inclusion in the pool, the owners of the other, Powers 1, have not yet agreed to enter the pool.

(d) *Effect of Permeability Variations.*

A point of paramount importance in gas cycling is the degree of homogeneity of the sand. It is recognized that model studies provide only approximate solutions, as they are generally based on uniform permeability and porosity, which never prevail in practice. The worst condition is met when very open and continuous sand beds occur in a series of tighter sands.

In Sheridan an early break-through of dry gas occurred in two wells,

Goodrich Unit No. 1 and Plow No. 10, indicating either (*a*) channelling through more permeable stringers, or (*b*) the reservoir contains less gas than volumetrically computed. A three-dimensional diagram showing an analysis of the permeability of the productive intervals of the various wells in milidarcy feet over 5-ft. intervals was prepared. This showed that there are two zones having higher than average permeability in the L sand. For the purpose of these computations all sand having permeability in excess of 1 mD. was assumed to be productive. The interval of highest permeability fluctuates with respect to the sand top over a vertical interval of approximately 15 ft. This study indicated that Plow 10 and Goodrich Unit No. 1 are both located in high-capacity areas, which probably explains the more rapid advance of the injected gas towards these wells. The effect of persistent permeable stringers on the content of the gas produced can be estimated according to a method described in a paper by Hurst and Van Everdingen.[23]

(e) *Physical Data of the Reservoir.*

The " L " zone was selected for cycling first for the following reasons: (1) permeability was more uniform; (2) the distillate content was greatest and consequently plant returns will be better; (3) productive capacity of wells was greater; (4) dry gas would be available for sale sooner than with simultaneous cycling; (5) the experience gained can be applied to other zones.

The area of the L sand is 7740 acres, of which 95 per cent is under unit operation. The full thickness of gas filled net pay on the crest is 40 ft., decreasing gradually to zero at the edgewater limit. The average porosity is about 18 per cent, the connate water is estimated to average 30 per cent, the permeability ranges between 1 and 8 mD in 45 per cent of the net acre feet of sand, the rest having a greater permeability, with some peaks of 50 up to 100 mD having been measured in cores.

The gas samples showed a relatively high content of 78 brl of butanes plus per million cu. ft. of gas. Propane recovery is made dependent on the market, at present amounting to about 19 per cent of the butane plus.

The original reservoir pressure was 4180 p.s.i. and temperature 260° F at 9135 ft.; it has probably declined slightly, but exact figures cannot be given, since, on account of the tight sand conditions, a complete build-up test to reservoir pressure takes a long time. Moreover, experience showed that mechanical equipment placed in dually completed wells to allow subsurface-pressure measurements frequently failed when being manipulated at the high pressures and temperatures present in Sheridan. Thus pressure information until after the conversion to single-zone completions in 1947 is meagre. The injection pressure measured at the surface averaged 4540 p.s.i.; therefore at the depth of the L sand it would be about 5300 p.s.i. The average bottom-hole flowing pressure of producing wells was 3350 p.s.i., leaving an average pressure differential of almost 2000 p.s.i. between injection and producing wells.

After completion of cycling the gas pressure in the sand will be allowed to drop, causing the wet gas still occluded in the tighter sand layers to expand and enter the gas stream to the wells and the plant. Thus a further amount of the condensable products will be recovered and the gas be available for

sale. Gas processing has been assumed to become uneconomic when the formation pressure reaches 1500 p.s.i., but dry gas sales will still be possible.

Other zones of importance are the " H " and the " P5–Q " sands, of which the last named certainly will be cycled. The productive area of both is slightly larger than the " L " sand, but the net sand thickness of the H is less. The " P5–Q " has an average thickness about three times that of " L," but lower porosity and permeability, and a much smaller condensate content; 42 brl per million cu. ft.

Several other sands, having smaller reserves, will be exploited by stripping the gas of its gasoline content without re-cycling the dry gas. The entire productive life of the field is estimated at over 30 years.

(f) *The Gasoline Extraction Plant* (Fig. 14).

This is of the high-pressure absorption type; it is designed for a maximum throughput of 100 million cu. ft. of gas per day with a compressor capacity of 5600 h.p. (7 × 800 h.p.) to repressure the gas for injection. Since closing in the P5–Q sand and until corrosion troubles are overcome the actual quantity being processed is about 79 million cu. ft./day from which about 6000 brl/day of liquid products are obtained, but it is expected to increase this on completion of the two additional output wells.

The items of equipment comprising the absorption and liquid products recovery unit are briefly as follows :—

Two 16-tray 1800-lb absorbers; a 20-tray reabsorber; a 27-tray still; a distillate stripper with 15 trays; a rectifier with 30 trays; a de-propanizer with 36 trays; a debutanizer with 40 trays; a de-isobutanizer with 70 trays, and a de-isopentanizer with 70 trays. Auxiliary facilities consist of three 500-h.p. water-tube boilers and three 800-h.p. gas-engine-driven generators.

Condensate Recovery Processes.

While it is important to avoid subsurface losses of condensate, so it is just as important to install efficient surface plant for stripping the gas.

Before the advent of cycling operations, distillate was extracted from the well production by means of surface separators, in one or preferably several stages, with or without a gasoline-recovery plant. With cycling it is obviously advantageous to keep the pressure of the first stage of separation as high as possible in order to reduce compression costs. Also in order to increase the distillate yield the practice of cooling the well effluent before separation has been widely adopted. Cooling is affected by use of either one, or usually a combination, of the following methods : water or atmospheric cooling coils, heat exchange with the stripped gas, the Joule–Thomson cooling effect of the gas in expanding between well-head and separator pressure, and artificial refrigeration by ammonia or propane-expansion plants.

Studies have been made to determine for various reservoir effluents the pressure and temperature at which optimum distillate recoveries could be obtained. A typical report on this subject is one by Buckley and Lightfoot [4] from which three curves have been taken (Figs. 15 and 16) to show the effect of separator temperature and pressure on the yield of condensate from a reservoir effluent. The calculated composition of this gas (from

Table IV [4]) is given under "C" in Table I; it is a rather lean gas. The pressures and temperatures refer to those of the first stage of separation.

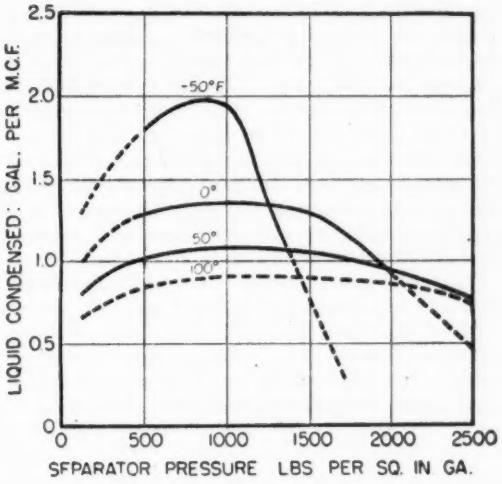


FIG. 15.

EFFECT OF SEPARATION PRESSURE ON GROSS LIQUID YIELD AT VARIOUS TEMPERATURES.

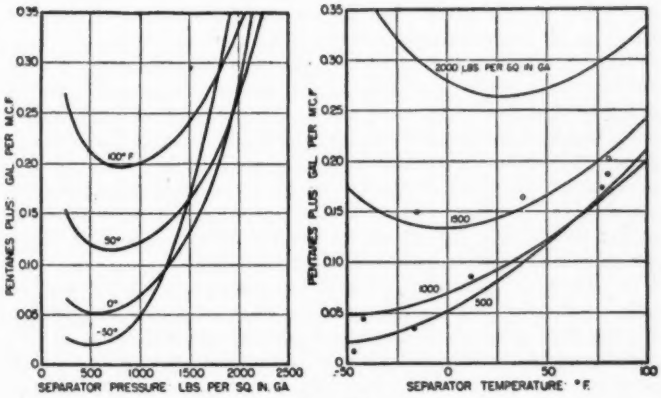


FIG. 16.

EFFECT OF SEPARATION PRESSURE (*left*) AND SEPARATION TEMPERATURE (*right*) ON PENTANE PLUS CONTENT OF RESIDUE GAS AT VARIOUS TEMPERATURES.

Fig. 15 shows the large increase in recovery to be obtained by cooling below 0° F. This degree of cooling will require measures to avoid hydrate forming, which question is touched upon below. In the design of recovery

plants, the composition of the residue gas, rather than the amount of liquid condensed, is the best criterion of efficiency. Fig. 16 shows two series of curves; that on the left gives the amount of pentanes plus in the residue gas plotted against the temperature for various separator pressures, and that on the right the same factor plotted against pressure for various separator temperatures. In the normal range of separator temperatures, optimum pressures for lowest pentane losses usually lie between 800 and 1200 p.s.i. depending on the quality of the reservoir effluent.

Plants based on cooling and stage separation, denoted as P.D. in Table III, are still used for small-capacity installations because of their relative simplicity and low capital cost, but most modern installations are of the absorption type. Absorption plants have the advantage of greater extraction efficiency and higher operating pressures with consequent reduction in compressor horsepower for re-injection.

The first high-pressure absorption plant built specifically for cycling operations was erected at the Agua Dulce field in 1939. It operates at 1200 p.s.i. Since then operating pressures have increased and absorption pressures of 1800 to 2000 p.s.i. are quite normal in modern practice (Table III). They differ from the ordinary natural gasoline type of absorption plant mainly in the higher pressures used in the absorbers. The saving in compressor investment offsets by a substantial margin the extra cost of absorbers and piping for the higher pressures. The absorption process is particularly well adapted to large installations with complete stabilization and fractionating equipment.

The absorption oil is usually a heavy kerosine fraction (mineral sea oil) with a short boiling range of the order of 480° to 600° F. The closer it approaches the specific gravity of the fractions to be absorbed, the more efficient the process will be, the limit being fixed by the tendency for the absorption oil to be taken up itself in the gas, which tendency increases markedly with higher pressures. This is a retrograde vaporization effect occurring in the reverse direction to the process of retrograde condensation previously described. In some plants the gas is given a second stage of absorption to recover the kerosine which has become vaporized in this manner by introducing a heavier grade absorption oil in the upper part of the column. This loss of absorption oil by vaporization becomes quite appreciable at pressures around 2000 p.s.i. It can be counteracted by increasing the specific gravity of the oil, but this reduces the efficiency of absorption and requires higher oil-circulation rates.

The amount of lean oil required for extraction of a fixed percentage of butanes will only vary about 10 per cent over the range from 1000 to 2000 p.s.i. absorber pressure, being a minimum at about 1400 p.s.i. This can be explained by the fact that while, with increased pressures, the volume of lean oil required to absorb the butanes plus increases, it is more than counteracted by the increase in effective volume of the lean oil due to the rapid absorption of methane, ethane, and propane from the lean gas in the first few trays of the absorber. This increase in volume at 2000 p.s.i. amounts to as much as 91 per cent. The expansion of the lean oil in no way reduces its efficiency as an absorbing medium. However, over 2000 p.s.i. the amount of lean oil required for absorption of the butanes plus increases more rapidly and will more than offset the favourable effect of the absorp-

tion of the methane and ethane; this, together with the loss of absorber oil due to "retrograde vaporization" may set an upper limit to absorber pressures in the neighbourhood of 2500 p.s.i. There is an interesting article on this aspect by Wade [24] entitled "High-pressure absorption."

The modern absorption plant consists of the following main sections :—

Raw condensate separators, from which the gas passes to the *High pressure absorbers*, with scrubbers on the inlet gas and residue gas sides.

Compressors for re-injection of residue gas.

Rich oil and condensate flash tanks. The separator condensate and the rich oil from the absorbers are flashed to a pressure close to atmospheric, either together or in separate systems. Pressure stages depend on liquid composition, but are usually three in number in the range of 600, 200, and 35 p.s.i. The flashed gases from each stage go to a scrubber, that from the first stage being compressed for injection. The gas from the other two stages is compressed to a pressure of from 450 to 600 p.s.i. and passed to the *Reabsorber*. Condensate and rich oil from the third stage flash, including also the rich oil from the reabsorber, after passing the heat exchangers, goes to the

Distillation and stabilization system; here by means of distillation and fractionation with appropriate refluxing, the plant products are split, if desired, into propane (liquid petroleum gas) normal and *iso*-butane, *iso*pentane, natural gasoline, and mineral seal oil, a proportion of the latter being used for the lean oil charge to the absorbers.

Natural-Gas Hydrates.

Freezing troubles encountered in high-pressure natural-gas systems are usually caused by a class of compounds called "Gas hydrates." A hydrate is a chemical compound in which water is present in fixed and simple molecular proportions.[25] Common examples are gypsum ($CaSO_4 2H_2O$), copper sulphate ($CuSO_4 5H_2O$), washing soda ($NA_2CO_3 10H_2O$), etc.; the combined water is known as "water of crystallization." Gas hydrates belong to the same family and in general have similar properties, but they are not stable above 32° F except at super-atmospheric pressures. The temperature below which they form rises rather steeply with increased pressure, especially in the lower pressure ranges. These temperatures are appreciably higher than the corresponding freezing point for water.

In addition to certain temperature and pressure limits for formation of hydrates it is necessary for a certain quantity of water to be present. As most natural gases are saturated with water vapour at the reservoir conditions, any decrease in temperature due to choke expansion or to precooling of the gas in the recovery plant (or increase in pressure due to compression) will cause some water vapour to liquefy and become a potential hydrate former. These compounds can be a serious nuisance and a source of danger at many points in the lines, separators, high-pressure absorbers, and compressor plants of a cycling system and steps must be taken to eliminate them.

Gas hydrates may not form immediately the boundary conditions are passed, but, as is common with supersaturated solutions, they may drop

out suddenly at some spot in the system due to restrictions in lines, pulsations of compressors, etc. They form as a white microcrystalline mass resembling snow. Methane, ethane, propane, and *iso*butane all form hydrates probably consisting of six or seven molecules of water per molecule of gas. Other gases often present in natural gas, such as carbon dioxide, hydrogen sulphide, and methyl mercaptan, also form hydrates. Normal butane and higher hydrocarbons do not form hydrates under normal operating conditions. All hydrates exhibit a definite vapour tension of

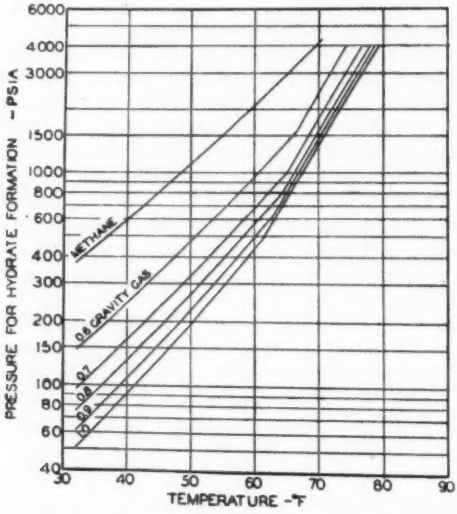


FIG. 17.

PRESSURE–TEMPERATURE CURVE FOR HYDRATE FORMATION.

water and therefore tend to effloresce when the water vapour above the hydrate is less than its vapour pressure, enabling them to be removed by a relatively dry gas stream.

The conditions for their formation have been studied by several workers; publications by Katz [26] and Katz and Carson [27] being particularly valuable contributions. Fig. 17 [26] shows pressure and temperature limits for natural gases of various densities below which hydrate formation may take place.

Methods for prevention of hydrate formation can be summarized as follows :—

1. *Increasing the temperature above the melting point of the hydrate. This method is commonly used for meters, regulators, and pipelines above ground. It cannot be used where it is desired to operate at low temperature for increased distillate recovery.*

2. *By reduction of pressure; not applicable in cycling operations.*

3. *Change of composition of the gas mixture by reduction of water-vapour pressure so that the water dew point of the gas is always lower than the operating temperature. This is the method most commonly applied in cycling operations, water vapour being extracted from the gas as soon as*

possible after it leaves the well head by hygroscopic liquids, such as calcium-chloride brines or hygroscopic solids, such as silica gel. Means for regenerating the brine of the silica gel must be provided.

4. *Bottom-hole chokes have also been used to eliminate the freezing of well-head connexions by removing the point of sudden expansion to a point where temperatures are higher.*

5. *The use of anti-freeze solutions, such as alcohol, or inhibition by introduction of ammonia gas have been used successfully but are expensive.*

Economics of "Cycling."

In the ultimate analysis the decision whether to return gas to the reservoir or to produce it by pressure depletion is essentially a question of economics. It is dangerous to generalize, and the case of each reservoir must be judged separately on its own merits, after sufficient data have been assembled and a careful estimate of probable reservoir performance has been made. The more important facts which must be ascertained and taken into account when deciding the exploitation policy, can, however, be enumerated.[28] These are :—

1. *Whether the field contains distillate only or distillate together with an oil column.*

2. *Physical properties of reservoir fluid in relation to reservoir temperature and pressure, that is whether on pressure drop the retrograde region will be entered, and if so the probable extent of the subsurface loss of liquid products if pressure is not maintained.*

3. *The size of the reserves in place expressed in terms of recoverable products. This is a function of sand thickness, effective porosity, reservoir pressure, the compressibility of the reservoir fluid, and recoverable G.P.M. of the reservoir fluid.*

4. *Productivity of the wells. This will govern both the number of output and injection wells required to sweep the reservoir in reasonable time. Spacing of output wells is always much wider than would normally be necessary in a crude oil, sand type field of comparable permeability, due to the low viscosity fluid and single-phase flow in a cycled reservoir. Spacings of the order of 250 to 640 acres/well might be considered as normal limits.*

5. *Permeability variation. This controls the degree of by-passing of of the gas. A distinction should be made between the macroscopic coverage of the sweep, chiefly governed by the arrangement of the input and production wells, and the macroscopic coverage due to local permeability variations, either horizontally or vertically, within the sand body. Lack of data usually makes it difficult to estimate the permeability variation with accuracy.*[29] *For macroscopic coverage a figure of 75 per cent is often taken, if a better figure, based, for instance, on electrical models, is not available. These factors must be applied to the calculation of the reserves in place mentioned in* (3).

6. *Degree of natural water drive, if any.*

7. *Field development and operating costs; these are mainly dependent on depth, well spacing, pressures encountered, and corrosion problems.*

8. *Plant installation and operating costs. Information on this question*

is not generally published. From what can be learned plant installation costs in recent years have varied from about $30,000 *up to* $60,000 *per million cu. ft. of installed capacity for modern absorption plants, dependent on size and degree of fractionation desired in the plant products. As a rough guide a high-pressure plant of* 100 *million cu. ft. per day capacity designed for re-injection at around* 4000 *p.s.i. and with complete fractionating equipment would cost in the neighbourhood of* $4·5 *million not including the field system. For maintenance cost a figure of* 5 *per cent of the capital cost and for annual labour cost* 8 *per cent of the same amount are considered useful figures for estimating purposes in the U.S.A.*

9. *Market considerations. This is a very important factor in the decision. If no market exists for the gas, conservation rules in the U.S.A. usually make it impossible to produce the field unless the gas is returned to the formation. If a lucrative market exists for dry gas, the delay in receipt of this revenue must be offset against the increased condensate recovery expected from "cycling."*

10. *A final consideration is the ability to interest all the companies and lease holders concerned in any reservoir, or at least the major proportion of them, in any reservoir, in a pooled cycling operation.*

In general as a rough guide, condensate fields yielding recoverable butanes plus of about 1 gal per 1000 cu. ft. form the lower limit for profitable cycling. Lower recoveries may afford worth-while stripping projects when there is a good market for the residue gas. Size of plant is largely dependent on the size of the reserve; consistent with this, the larger the plant the lower the cost per unit of capacity and the lower the unit operating cost. Payout times of 2½ to 4 years with at least a further 5 years of profitable operation are normal requirements. An absorption plant of smaller capacity than 35 million cu. ft. per day is seldom found to be a commercial proposition due to the disproportionately high cost of the auxiliaries and the high running costs per unit of throughput. However, for smaller reserves a high-pressure stripping operation, with or without deep cooling, and the necessary compressor capacity might prove worth-while.

In designing the cycling system, it is a wise precaution to make the plant sufficiently flexible so that, should at any time economic factors make it necessary, it can be readily simplified to a stripping proposition and surplus plant transferred elsewhere without entirely disrupting the system.

Cycling near Dew-Point Pressure versus *Pressure Depletion followed by Low-Pressure Cycling.*

An interesting case has been made by Standing, Lindblad, and Parsons [15] based on laboratory results and calculations using data from an actual field example, which shows that, compared to normal cycling at around dew-point pressure, somewhat greater recoveries of butane plus are to be obtained by allowing the reservoir pressure to drop to a low order, in the range of 400 p.s.i. and then revaporizing the butanes plus deposited by retrograde condensation and sweeping them out of the reservoir with a low-pressure dry gas sweep. They do not go into the economic angle of this proposition, and there is no field experience to support their contention. The suggestion has consequently given rise to a good deal of controversy,

and among others articles have appeared by Bennett [30] and Arthur.[31] Both these authors give various considerations which tend to show that the expected greater recoveries are not only speculative, but, even if achieved, may not result in greater present-day worth of the total profit. Such factors as the larger number of wells required for the low-pressure sweep, delay in revenue receipts, the uncertainties of recovering the condensate deposited in the finer interstices of the reservoir, and the possibility, with high-pressure cycling, of recovering a further amount of condensate by pressure depletion after completion of the normal cycling, are all instanced. The economic case is well presented by Arthur, who has worked out expected present-day profits on various bases with examples taken from the original author's report.

Conclusion.

In the foregoing review an attempt has been made to cover, as adequately as possible within the space available, one of the most interesting of modern reservoir engineering applications. Each of the chapter headings is capable of providing enough material to form the subject of an individual paper. This is demonstrated by the wealth of papers on the various facets of distillate field exploitation to be found in the American literature, some of these, although still a relatively small proportion of the total, are listed in the references. It was thought that, as this is the first time the problem of production from condensate-type reservoirs has been introduced to a meeting of this Institute, a general paper would be more appropriate. The authors hope that this review will serve to arouse interest in the subject and that in the future more papers will be forthcoming on some of the individual aspects of condensate fields and their production technique. This may not be possible until cycling projects become familiar practice in areas where British companies are operating, but it is believed that that day will lie not so far ahead.

The authors are indebted to the N.V. De Bataafsche Petroleum Maatschappij for permission to publish this paper and to the Shell Oil Inc. for permission to include the information on the Sheridan field. They also wish to thank colleagues at The Hague for their co-operation : in particular, Mr Siccama[32] for providing information and Mr Hols, Mr Van den Berg, and Mr Wennekers for assistance in preparing it for publication.

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Discussion.

The Chairman (Mr T. Dewhurst): I have described the paper as interesting, important, and lengthy, and I am sure you will agree with that description.

The authors deal mainly with the physics, mechanics, and economics of production from distillate reservoirs. I can only say a word or two as to the geological setting of the operations. It is stated that important data, including, *inter alia*, sand thicknesses, porosities, variation in permeabilities, and degree of natural water drive, if any, should be ascertained before

framing an exploitation policy. Of course, wells such as have been referred to are very deep and very costly, and if only a few such wells, very widely spaced, are drilled on a very big structure, it may be possible to obtain only scanty and very inadequate evidence of the thicknesses, porosities, and permeabilities of the sands or other reservoir rock throughout the whole of the structure. Moreover, it would almost certainly be necessary to frame an exploitation policy long before any evidence appeared as to the existence of a natural water drive.

PROFESSOR V. C. ILLING : The paper we have listened to is one of fundamental importance, and I want to congratulate not only the authors on their treatment of the subject but also the Institute on having a paper of such deep interest brought to our notice. The authors have had to use considerable discrimination in compressing a subject with so many interesting aspects, and I would like to thank Mr Stevens for the way he has brought out the high-lights of the paper in his presentation of the work.

As I listened to his remarks I could not help thinking of the tremendous strides which had been made in the last decade in the study of reservoir behaviour and the efficient extraction of distillate fields. How different would have been the results in such fields as Turner Valley if the physical conditions in the reservoir had been fully appreciated at an early phase.

Once you allow pressures to decline in such fields to a point at which condensation of distillate occurs within the reservoir, you are inducing an entirely new set of conditions which will render the recovery of the condensed distillate far more difficult as an economic proposition. Such condensate would normally tend to occur as annuli resting on connate water at the points of contact of the sand grains. Scrubbing of this distillate by gas drive would be difficult unless the distillate were first concentrated by gravitational segregation, which seems unlikely unless the condensate was present in considerable bulk. Nor does it appear likely that efficient recovery could be obtained by scrubbing the reservoir with gas at low pressure.

The authors' references to experimental model studies raised several problems of the validity of the results of such work. Experiments of these types had to make a number of assumptions, and their results were valid only as long as these assumptions held true. In the case of most reservoirs the question of the continuity and uniformity of the permeability was probably the biggest assumption. The speaker would like to enquire how far varying permeability in a reservoir would affect its treatment in practice. Would it be preferable to re-inject gas at the low-permeability or at the high-permeability end of the reservoir, or should movement be induced parallel to the zones of equal permeability ?

Another interesting point in pressure maintenance on which the speaker would like further information is whether there is any detectable tendency for the re-injected gas, which would presumably be lighter than the reservoir gases, to move preferentially upward in the reservoir, or does it expand from the input wells with little noticeable relation to structure.

One interesting speculation bearing on the problem of oil and gas migration is worthy of notice. Presumably these gas fields containing distillate change their conditions during the processes of sedimentation. As the

reservoir becomes more deeply buried under the load of sediments, pressure and temperature increase and the whole hydrocarbon content becomes vaporized. This illustrates the importance of gas as a driving force in migration.

In conclusion, the speaker would like to express his pleasure in listening to a type of paper which will, he feels, be welcomed by a large body of the Institute.

MR A. BEEBY THOMPSON : My first experience of these distillate wells was in Russia, about the year 1900, when wells in the Surakhani field yielded something of the order of 50,000 to 60,000 g.p.d. of distillate oil. These wells were allowed to flow wild, and the oil was destroyed by burning, as there was no market for products lighter than kerosine, and operators were then unable to shut off the sources before deepening for heavy oil.

In the Kettleman Hills field, which came in as a distillate field, it was quite impossible to carry out any organized drive, because the land was so cut up into separate holdings that operation was at that time out of the question. It does seem essential in connexion with any distillate schemes to ensure unified effort; otherwise the regulation of edge water is impossible.

Some three weeks ago I was on the Katy field with some of the staff of the Humble Oil Refining Company, who explained the working of the field. Those in charge of the field exhibited plans showing the position of intake and out-take wells. The operations there are perhaps the biggest yet attempted. I should very much like to know whether Mr Stevens thinks that the influence of faults on structures is likely to seriously prejudice results. In the Katy field the dry gas is injected down dip in the structure and the rich gases are removed at high points, but doubtless the reverse operation might prove in some cases efficacious.

The problem of casing corrosion is one of great importance. Mr Stevens mentioned that investigations had led to considerable success in the case of inhibitors. In these very deep high-pressure fields there is no doubt that corrosion could cause serious consequences unless means of combating the trouble are found.

In these distillate fields a considerable quantity of gas is needed for fuel on the operation and a certain amount is sold. The treated gas returned to the structure is thus substantially less than that removed, but could be made good by using dry or treated gas from other fields. Another interesting feature of the process is the isolation from the distillate of the fraction used as a solvent for the gasoline.

THE CHAIRMAN : I will mention now a point which has troubled me for a little time. Throughout the world oil has been produced from a great many fields, and in most cases, following the extraction of the oil, gas caps are formed, which expand in the course of development. As time goes on there will be an increasing number of fields from which most of the easily recoverable oil has been extracted, leaving enormous gas caps which contain large volumes of oil caught up, particularly in tight layers of sand, for example. I have often wondered what will be the ultimate fate of these fields from which most of the recoverable oil has been extracted, but in which enormous volumes of oil still remain in great gas caps.

MR STEVENS, replying to the discussion, said: With regard to the first point you made, Mr Chairman, we never know enough about the porosity and permeability of practically any field with which we have to deal. There are many gaps in our knowledge, and we have to extrapolate or interpolate, or even just plainly guess in many cases; thus there is always great possibility of error due simply to lack of adequate data.

Turning to the question of the gas caps, which the Chairman also raised, presumably these gas caps will be at very low pressure by the time the primary oil is exhausted, and I do not think that much could be done by a gas drive, for the driving gas would just go through the spaces already filled with gas. There is another method of secondary recovery, namely, that of water drive; if the permeability is reasonable and other conditions are favourable, it might be possible to subject such a field to a water drive and push both oil and gas up structure again. The gas production would not be very large, because of the low pressure, but at least we might be able to recover a further proportion of the oil which is undoubtedly left behind after the pressure-depletion stage.

Replying to Professor Illing's remarks about the permeability and the effect it has on the model studies; of course in all these model studies we do make certain assumptions, which are listed in the paper under the sub-heading "(*b*) Model Studies." By far the most important is that we usually assume that the horizontal permeability is uniform throughout the reservoir. That is, indeed, a big assumption to make. In the potentiometric model allowance can be made for variable permeability if there is sufficient data available to warrant such a correction, but this is not often the case. The other assumptions are not so important. One is that the relative permeability effects may be neglected, *i.e.*, since we are dealing with dry gas and wet gas, there will not be much change in the permeability of the sand to the dry gas compared with that to the wet gas. Next, the viscosity difference between the driving and the driven fluid may be neglected, for it is not very great. We also assume that gravitational effects due to difference in density of the two fluids may be neglected and that the compressibility of the fluids may be neglected, since the pressure differentials are small compared with the absolute pressure. Of these five assumptions, the one concerning permeability is so predominant that I do not think we have to worry very much whether the difference in density of the two gases would have much tendency to cause a gravitational flow of the heavier gas down the structure while the lighter injected gas was concentrated in the upper part of the sand. Again, when considering permeability variations, these are usually most marked in the vertical direction, we generally find in most wells a few high-permeability streaks and a lot of low-permeability streaks and some definite barriers such as thin shale breaks. It is possible perhaps at a certain stage to eliminate a high-permeability streak by means of a packer, if it is so permeable that it is causing by-passing. But presuming the range of permeability is not too great, we have to take the chance of putting the gas in and hoping for a good recovery. A paper has been presented in the United States by Hurst and Van Everdingen, two Shell engineers, dealing with the effect of different permeabilities in the vertical range. The paper is highly mathematical, but the authors do give a basis on which these effects can be calculated to a certain extent.

Professor Illing asked about the effects of injecting from low to high permeability and *vice versa*. Apart from the fact that the biggest variations are usually in the vertical range, the question of the injection pattern has also to be considered, because, if for instance you decide to adopt terminal injection, you have the choice of the two ends of the field. If you are injecting from the low-permeability end to the high-permeability end, or *vice versa*, I do not think the total pressure differential would vary very much. I have a feeling, however, that you may prefer to inject from the low-permeability end for two reasons: (*a*) because you can take your production from the high-permeability wells at lower drawdowns, thus helping to avoid the deposition of condensate around the well bore, and (*b*) the drying effect of the injected gas may improve the permeability of the low-permeability injection wells as was the case in Sheridan. Of course, a somewhat greater injection pressure or a larger number of injection wells would be required to achieve the requisite injection rate, thus involving more capital investment. Actually injection and withdrawal points are largely governed by structural considerations, and you have to consider which injection method seems to suit the structure best.

As to the possibilities Professor Illing mentioned concerning migration effects, there is just one thought that I would like to put forward. Of course, you may find residual oil in some structure which you may think has come originally from a deeper source, having migrated upwards in the gaseous phase, together with the heavy ends it contains, which heavy ends, as a result of retrograde phenomena, have been deposited at a certain point. That might be possible, provided the heavier ends are not too heavy. If they are indeed heavy, it is doubtful that they could ever have been in the gaseous phase, for that would call for the application of tremendously high pressure and temperature; in other words, if they have the nature of normal crude oil, they would have had to be very deep seated indeed to have been converted into the gaseous phase after deposition. Thus, the matter is governed very largely by the composition of the fluid found.

Reference was made by Mr Beeby Thompson to the Katy field, which is, indeed, the largest recycling project in the United States at the moment, with a daily throughput of 450 million cu. ft. of gas, I think; and it has some faults. I have not studied the geology of all these fields; but for instance the Sheridan field is not faulted. When we define a reservoir we must remember that if it is limited on any side by a fault, then that fault marks one of the boundaries of that particular reservoir; if there are five or six faults we may have five or six separate reservoirs to consider, provided the faults form pressure seals. I believe that in the Katy field there are such effects. The only way in which to consider such a field is to treat each fault block as a separate injection problem.

In conclusion, I would like to say that your reception of our paper has been very gratifying to me, as I am sure it will be also to Mr Boots.

Vote of Thanks.

The Chairman: At the end of the paper the authors acknowledge their indebtedness to their companies and also to their colleagues at The Hague;

we who have heard the paper presented and discussed would like to share in that expression of indebtedness.

I am sure you would all wish me also on your behalf to express thanks to the authors for this very valuable contribution to our Proceedings and to our *Journal*; and particularly to thank Mr Stevens for the excellent manner in which he has presented the paper.

(The vote of thanks was heartily accorded, and the meeting closed.)

HYDROCARBON RESEARCH GROUP.

Report for Year Ending October 1948.

During the year the synthesis of almost all the hydrocarbons originally proposed has been completed (a list of these is given at the end of this report), and the hydrocarbons will be passed on to the Spectroscopic Groups for study. It will be remembered that the hydrocarbons were chosen in order to enable a study to be made of the correlation of spectra with structure, and the spectroscopic results will be awaited with interest. The installation of adequate fractionating equipment at Bedford College and at the University of Birmingham has considerably facilitated progress. Both intermediate and final products have been fractionated, thus ensuring the final purity.

As the result of the near completion of the original programme, the research centres have submitted programmes for future work. These programmes which were adopted by the Hydrocarbon Research Group aim at a more fundamental approach to the problem of hydrocarbon synthesis and at an extension of our knowledge of unsaturated hydrocarbons. At Bedford College Professor E. E. Turner and his collaborators will investigate particular aspects of routes to hydrocarbons as a class rather than as individuals and will study the scope of the reactions involved. Particular attention will be paid to reactions of organic–metallic compounds of magnesium and lithium on amides of various types, to halogenation of particular types of paraffins and to the interaction of dihalogen compounds $Hal.(CH_2)_x.Hal$ and their branched-chain analogous with sodioaceto-acetic or malonic esters. Dr Hickinbottom at Queen Mary College will continue his studies of the oxidation of olefins, and his work on the structure of poly*iso*butylene and will, in addition, investigate methods for the synthesis of saturated and unsaturated aliphatic hydrocarbons containing highly branched structures. This work is co-ordinated with the work of Dr Porter at Birmingham University, who will investigate the reactions of olefins with a view to developing methods of determining the position of the double bond and of estimating the amounts of different types of olefins present in mixtures. Dr Porter's programme also includes the synthesis of pure hydrocarbons of known structure for the purpose of determining accurate physical-constant data.

The work now in hand is not only wider in scope than that previously carried out but it also represents a marked increase in the amount of work attempted. This has been made possible by the fact that the research work sponsored by the Hydrocarbon Research Group has attracted other research workers to the schools at which such research is prosecuted. Thus at Queen Mary College—where the Institute-sponsored programme supports one Research Fellow—six research workers are engaged on studies integrated within Dr Hickinbottom's programme. Similar conditions exist at Bedford College and at the University of Birmingham. This development of academic interest in hydrocarbon chemistry is not confined

to these colleges, and the Institute and the sponsoring companies can now be assured that field of hydrocarbon chemistry—so long neglected in this country—will attract increasing attention from academic workers.

The report of the Spectroscopic Panel is equally encouraging. Good progress has been made in all the fields selected for study, and commercial development of certain of these is gradually being achieved. Work has continued on the development of detectors, on improvements in the cathode-ray oscillograph spectrometer, and on the construction and operation of grating instruments of high resolving power. New work on polarized infra-red radiation, on spectra at low temperatures, and on change of spectra with change of state has been reported. Development of a recording Raman spectrometer and a recording ultra-violet spectrometer have been reported.

Here again the work sponsored by the group has had its effect in encouraging other work in this field. The marked " hydrocarbon " bias of much of the research work now being conducted in the Physical Chemistry Laboratories at Oxford is shown in the presidential address of Professor Hinshelwood to the Chemical Society. The development of the reflecting microscope, and the use of this instrument in conjunction with infra-red and ultra-violet spectrometers found reference in the anniversary address of the President of the Royal Society.

It is a pleasure to record two further developments within the year, both of which promise to enhance the value to the Institute and to the industry of the hydrocarbon research programmes. During the year, conversations with the Director of the Chemical Research Laboratories at Teddington (Professor R. P. Linstead) indicated that mutual benefit might result from a more detailed exchange of views. Council approved that Professor Linstead should be invited to attend the Hydrocarbon Research Group as a guest member and nominate members of his staff to the various panels. This invitation Professor Linstead has accepted, and his experience and enthusiasm will be of the greatest value to us.

The increasing interest in the mass spectrometer and its obvious applications to the petroleum industry have led during the past two years to the formation of a group of those companies and universities intending to instal such instruments. The obvious desirability of establishing some means of ensuring a supply of satisfactory hydrocarbons for calibration purposes and of providing a means of exchange of information led the group to approach the Institute for advice. As a result, a Mass Spectrometer Panel has been formed, and Mr Blears of Metropolitan-Vickers Electrical Co. has accepted the chairmanship of this Panel. Professor Linstead on behalf of the C.R.L. has agreed to undertake the supply of hydrocarbons in collaboration with members of the Hydrocarbon Synthesis Panel.

The recent development at the Chemical Research Laboratories of a group devoted to the preparation of organic compounds of high purity and to thermodynamic studies of such compounds will thus be linked to developments within the petroleum industry and will provide the United Kingdom industry with services comparable to those offered by the U.S. Bureau of Standards to the United States industry. It may well be that the development of thermodynamic, kinetic, and other fundamental studies of hydro-

carbons long discussed by the Hydrocarbon Research Group will thus be facilitated.

Dr B. W. Bradford (I.C.I. Billingham Division) was elected Chairman of the Hydrocarbon Research Group for 1948–49. Dr Bradford has been an enthusiastic member of the Group for several years, and under his able guidance the progress of the Group is assured.

Finally, I wish to record my appreciation of the work of Mr F. Gill (Chairman, Spectroscopic Panel) and Dr F. A. Fidler (Chairman, Hydrocarbon Synthesis Panel).

F. MORTON

APPENDIX.

Hydrocarbons Synthesized.

2 : 7-dimethyl octane	2 : 3 : 3-trimethylhexane
3 : 4-dimethyl nonane	4 : 4-dimethyloctane
4 : 5-dimethyl nonane	3 : 4-dimethyloctane
n-butyl*cyclo*pentane	2 : 3-dimethyloctane
2 : 3 : 5-trimethylhexane	2 : 3 : 3-trimethylheptane
2 : 4 : 6-trimethylheptane	2 : 8-dimethylnonane
2 : 2 : 4-trimethylhexane	2 : 2 : 6-trimethyloctane

REPORTS.

XX. Reactions of unsaturated compounds, Part VI.
XXI. Reactions of unsaturated compounds, Part VII.
XXII. Reactions of unsaturated compounds, Part VIII.
XXIII. A low frequency amplifier for use with thermocouples.
XXIV. A recording ultra-violet spectrometer, II.
XXV. Infra-red spectra and the solid state: measurements with polarized radiation.
XXVI. Intensities of vibration bands I. Bending vibrations of benzene derivatives and the dipole of the C–H link.
XXVII. Reactions of unsaturated compounds, Part V.
XXVIII. Some measurements on the absorption of centrimetric waves by liquid dielectrics.

Reports in Preparation.

Vibration spectra of hydrocarbons I. (Nearly ready for distribution.)
A recording spectrometer for Raman spectroscopy. (Nearly ready for distribution.)

(*a*) Change of spectra with change of state.
(*b*) Fine structure in the absorption spectrum of allene.
(*c*) Use of polarized infra-red radiation. (2nd report.)
(*d*) Comparison of thermocouples and bolometers.
(*e*) Performance of spectrometers from design data.
(*f*) Results on polarized infra-red radiation.
(*g*) Application to other fields of spectra obtained under I.P. sponsorship.
(*h*) Correlation and interpretation of spectra.
(*i*) Report on ultra-short wave measurements.
(*j*) Double beam infra-red spectrometer.

THE ANALYSIS OF GASES BY ABSORPTION.

By the LIQUEFIED GASES PANEL OF SUB-COMMITTEE No. 3—GASES AND LIGHT DISTILLATES.

In 1945 a general procedure for the analysis of hydrocarbon gases by low temperature distillation was published by the Liquefied Gases Panel of Sub-Committee No. 3 of the Standardization Committee.[1] Owing to the diverse forms of low-temperature distillation equipment in common use, it was not considered desirable to specify any one apparatus, and the Panel confined itself to giving a broad outline of the main principles involved and to listing the factors necessary for good fractionation.

Subsequent to the publication of the distillation procedure, the Liquefied Gases Panel, which is composed as follows :—

J. H. D. Hooper (*Chairman*) .	Anglo-Iranian Oil Co. Ltd.
N. E. Jones (*Deputy-Chairman*) .	"Shell" Refining and Marketing Co. Ltd.
L. Aston	Anglo-American Oil Co. Ltd.
R. J. Bressey	Shell-Mex & B.P. Ltd.
K. R. Garrett	Calor Gas (Distributing) Co. Ltd.
E. S. Squire	National Oil Refineries Ltd.
H. T. Straw	I.C.I. Ltd.

has turned its attention to another important aspect of gas analysis, namely chemical absorption methods of analysis. Consideration was first given to the possibility of laying down a standard procedure, but in view of the numerous types of apparatus available and the wide choice of reagents in common use, it seemed that such action would be premature, unless backed by a considerable volume of experimental work. It was therefore decided to follow the course adopted for low temperature distillation analysis, *i.e.*, to publish, for information only, a general account of absorption methods which would give an outline of a suitable apparatus with a list of typical reagents and some observations on the more important points of technique.

In so far as choice of apparatus was concerned, the task of the Panel was made difficult by the fact that the equipment for absorption methods of analysis is infinitely more varied than that used for low temperature distillation. Gas quantities, for example, may be assessed by measurement of volume changes at constant pressure, or pressure changes at constant volume; designs vary also according to whether large or small samples have to be examined, and furthermore, certain constituents such as butadiene, are not readily determined on conventional types of apparatus and require specialized apparatus. It seemed, in fact, that an account of absorption methods of analysis would, if at all comprehensive, be a book in itself, and that any form of shortened summary would be mainly notable for its omissions—the present article must inevitably fall in the latter category. The apparatus described is limited to the conventional Orsat-type equipment commonly used in the petroleum industry, and the few absorbing solutions mentioned are those most generally used. As such apparatus frequently includes equipment for determining certain constituents by combustion methods, these methods are also dealt with briefly.

In conclusion, it is emphasized again that this account, which is published for information, is not intended to give a comprehensive survey of absorption methods of analysis, and that the features dealt with in the limited space available are those which the Panel feels might be of value and guidance to analysts interested in this class of work. Comments and criticisms are invited, and suggestions as to aspects of the subject which might be omitted, modified, or dealt with more fully in any subsequent publication, and which would help to pave the way towards the formulation of a standardized procedure, will be particularly welcome. Such comments should be sent to the Technical Secretary of the Institute for consideration by the Sub-Committee and Panel concerned.

Principle.

The relative percentages of the various constituents in a gaseous mixture may be determined from the successive decreases in volume obtained on passing the gas through a series of solutions, each of which selectively absorbs one component of the mixture. In some instances, however, it is necessary to make allowances for the co-absorption by any one solution of any other constituents present in the gas mixture.

The following gases are commonly estimated in this way : carbon dioxide, carbon monoxide, oxygen, sulphur dioxide, hydrogen sulphide, and unsaturated hydrocarbons.

It is usual to include the estimation of hydrogen and paraffin hydrocarbons under this method, the apparatus being modified, as below, to include a combustion unit for the purpose.

Apparatus.

The apparatus in general use is of the constant-pressure " Orsat " type, which may be modified to suit special requirements. It consists essentially of the following components :—

1. *Burette.* Except in special cases (*i.e.*, in apparatus devised for the examination of very small samples), the burette should have a capacity of 100 ml, graduated from 0 to 100 ml and subdivided to 0·2 ml. It should be surrounded by a water jacket to maintain the temperature of the gas constant throughout the analysis, and connected at its lower end to a levelling bottle containing the confining liquid. Where maximum precision is required, the burette should be equipped in addition as follows :—

(*a*) Compensator vessel, contained within the water jacket. By balancing the pressure in the burette against that in the compensator, each time a volume measurement is made, corrections are automatically made for variations in temperature and pressure during an analysis.

(*b*) Stopcock,[2] with two bores, between burette and rubber connexion to levelling bottle. One bore has the normal diameter, while the other is constricted to permit sensitive control of the flow of confining liquid. Suggested dimensions are :—

Full bore	diam. 3 mm
Constricted bore	„ 0·125–0·15 mm
	length 2–3 mm

Note : Care must be taken when using the constricted bore to avoid obstruction by stopcock grease.

2. *A Stopcock Manifold*, by means of which the sample of gas from the burette can be passed in turn to a series of absorption pipettes.

3. *Absorption Pipettes.* The choice of suitable pipettes to contain the absorbents is important, as the success of the analysis depends upon efficient absorption. Good contact between gas and liquid is required, and a number of patterns are available which have been developed with a view to ensuring this. The usual forms are bubbler and contact types. In the former, the gas is dispersed into a stream of fine bubbles by means of a sintered glass plate ; in the latter, lengths of glass tubing are placed vertically

within the pipette to provide large surfaces of contact between the gas and the reagents. Contact pipettes should be used for sulphuric acid solutions, since they give more accurate and consistent results than the sintered glass bubbler-type for this reagent. Further recommendations as to the selection of the absorption pipettes are given under the section " Absorbing Solutions."

Additional equipment, which may also be incorporated, for the determination of combustible gases, is as follows :—

4. Explosion tube fitted with platinum electrodes.
5. Slow combustion pipette, fitted with a platinum spiral.
6. Copper oxide combustion furnace (gas or electrically heated).

Confining Liquid.

The choice of confining liquid is related to the accuracy of the analysis and to the type of apparatus used. Mercury is the best confining liquid where maximum accuracy is required, and should be used whenever possible. Certain routine analyses, however, such as may be required for plant control purposes, do not always call for extreme accuracy, and for these analyses it is often simpler and more convenient to use an aqueous confining agent. Mercury eliminates errors which might otherwise arise due to physical solution of gases, but it cannot be used for gases containing hydrogen sulphide or when bromine is employed as the reagent for determination of unsaturated compounds. If mercury is used as the confining agent, it is necessary to add a small amount of water (just sufficient to moisten the walls of the burette) to ensure that gas volume measurements are made under conditions of constant humidity.

Aqueous confining agents are in general use for routine analysis, the solubility of the gas under examination being reduced by using a suitable salt solution. A small amount of wetting agent is often added to keep the burette clean and to allow more uniform drainage. Solutions commonly used are as follows :—

1. Sodium chloride solutions in strengths ranging from 20 per cent to saturated and usually acidified with hydrochloric acid. The addition of a small amount of methyl red renders the liquid level easier to observe and provides visual evidence of the acidity.
2. Zinc sulphate (saturated solution).
3. 20–25 per cent sodium sulphate solution, acidified with 5 per cent sulphuric acid.
4. Concentrated calcium chloride solution.

The choice of confining solution to be used depends upon the nature of the gas to be analysed, and a solution should be selected which gives the minimum absorption of components from a given mixture. The loss of constituents can be lowered by saturating the confining liquid before use with a sample of the gas to be analysed, by shaking the gas and liquid together and allowing to stand at room temperature. Where routine samples are being analysed, sampling aspirators can be kept for the various types of gas. Care should be taken that contamination of a sample does not occur through use of an aspirator containing confining liquid which has been saturated with a component such as carbon dioxide, at a higher

concentration than in the sample to be analysed. Failure to observe this is a frequent cause of errors.

Absorbing Solutions.

A number of absorbents have been suggested and used from time to time, the selection of a suitable absorbent depending upon the nature of the gaseous mixture to be analysed and the apparatus available. Recourse must be made to the literature on the subject where special cases have to be met. Absorbents in general use in Orsat-type apparatus are as follows :—

Carbon Dioxide, Hydrogen Sulphide, and Acidic Gases.

The usual absorbent is potassium hydroxide solution (30 per cent w/v), used in a bubbler-type pipette and protected from the atmosphere by a thin layer of medicinal paraffin. Acidified cadmium acetate solution, or alternatively approximately 0·1*N*-iodine solution, in a contact-type pipette, may be used for the removal of hydrogen sulphide, prior to the absorption of carbon dioxide so that distinction may be made between these two gases. The iodine solution will also remove sulphur dioxide, if present. The cadmium acetate solution should contain 25 g of cadmium acetate per litre of 1 per cent by weight acetic acid.

Carbon Monoxide.

1. Cuprous chloride in ammoniacal solution. 500 g of ammonium chloride are dissolved in water and diluted to 2 litres. The solution is then heated to 60° C, 400 g of cuprous chloride added, and the whole well shaken up. After the addition of some copper turnings (approx 100 g), the solution is allowed to stand, in a stoppered bottle, until colourless. When required for use, the solution is diluted with one-third of its volume of ammonium hydroxide (sp. gr. ·880). The solution should be protected from the atmosphere whilst in the pipette by a ¼-in. layer of medicinal paraffin or transformer oil. Ammonia vapours evolved from the reagent should be removed by means of a pipette containing 10 per cent sulphuric acid prior to volume measurement.

2. Cuprous chloride in acid solution. 360 g of cuprous chloride are dissolved in 2 litres of hydrochloric acid (sp. gr. 1·18). This solution is also reduced by allowing to stand in contact with copper. It is sometimes recommended that 4·0 g of stannous chloride should be added to each 200-ml portion of reagent just prior to its use. After using this reagent, the gas sample must be passed into potassium hydroxide solution to remove acid vapours.

3. Suspension of cuprous sulphate and β-naphthol. This reagent is made up as follows :—

Cuprous oxide	20 g
Sulphuric acid (sp. gr. 1·84)	200 ml
Water, distilled	25 ml
β-naphthol	25 g

The acid is added to the water and allowed to cool. The cuprous oxide is placed in a porcelain mortar, the diluted acid added in small increments, and a suspension formed by thorough grinding. The β-naphthol is

added in a similar manner. The mixture is filtered through glass wool before use in a contact-type pipette, and is protected from the atmosphere by a thin layer of medicinal paraffin.

Absorption is more rapid than with ammoniacal cuprous chloride, but settling of the suspension tends to occur below 15° C and may cause trouble. This reagent will absorb olefins.

Oxygen.

1. Alkaline pyrogallol solution, used in a bubbler-type pipette. 15 g of pyrogallol are dissolved in 50 ml of warm water and made up to 200 ml with 30 per cent (w/v) potassium hydroxide solution. The solution is best prepared by running the potassium hydroxide into the pipette, inserting a glass tube, covering the liquid surface with a thin layer of medicinal paraffin or transformer oil, and then adding the pyrogallol solution through the tube, so that admixture takes place out of contact with the air.

This solution absorbs carbon dioxide, and this gas must therefore be removed from a sample prior to the determination of oxygen content.

2. Chromous chloride solution, used in a bubbler-type pipette. A solution of chromic chloride in 2*M*-acetic acid is prepared and then reduced to the chromous salt by means of zinc amalgam.[3]

This solution possesses the advantage that, when exhausted, it can be rendered suitable for further use by reduction with zinc amalgam. It can be used for the determination of oxygen in the presence of carbon dioxide.

Unsaturated Hydrocarbons.

The determination of unsaturateds in admixture with saturated hydrocarbons is a frequent problem in the analysis of petroleum products.

The choice of method, apparatus, and technique depends upon the nature of the gas to be analysed, the constituent to be determined, and the accuracy required, and only an indication of some of the more usual absorbents can be given here :—

Bromine. This reagent is usually used in 5 to 10 per cent concentration in water or potassium bromide solution. It is satisfactory only for the absorption of olefins; and its reaction with paraffins (especially the butanes), benzene, and mercury limits its applications. It is also necessary to remove, by alkali wash, bromine vapour evolved from the reagent prior to gas volume measurement.

Sulphuric Acid. Fuming sulphuric acid absorbs olefins, acetylenes, aromatics, and higher paraffins. By the control of the strength of sulphuric acid, absorption of unsaturated hydrocarbons only, in the presence of other hydrocarbons, may be effected. Contact-type pipettes should be used. The following examples are typical :—

(*a*) 65·0 $\pm$ 0·2 per cent sulphuric acid for the estimation of *iso*-butene in butane–butene fractions.

The acid is " fattened " before use by the addition of 5 ml/litre of tertiary butyl alcohol. Correction must be made for the slow co-absorption of normal butenes.

(*b*) 87·0 $\pm$ 0·5 per cent sulphuric acid for the estimation of

propylene in mixtures containing propane, propylene, and lower fractions.

(c) 98·0 ± 0·5 per cent sulphuric acid containing 3 per cent by wt of silver sulphate for the estimation of ethylene in the presence of ethane, or in mixed C_2–C_3 fractions after the removal of propylene.

Hofmann's Solution. This absorbent is made up as follows :—

111 g mercuric nitrate dihydrate.
133 ml nitric acid sp. gr. 1·41.
600 g sodium nitrate.
800 ml distilled water.

The absorbent may be used for determining total olefins in C_4 and lower fractions and for absorbing normal butene and butadiene in the presence of butane. A sintered glass bubbler should be used for this reagent.

Notes :

(i) *This reagent cannot be used in the presence of carbon monoxide or large quantities of hydrogen.*

(ii) *If* iso*butene is present it must be removed before passing gas into Hofmann's solution, as it interferes with the reaction, low results being obtained. A yellow precipitate is formed which clogs the sintered bubbler.*

Procedure.

The details of manipulation depend upon the apparatus in use, the skill of the operator, and type of gas to be analysed. The following give a general outline of the procedure and indicate the factors to be considered.

Sampling.

The chief sources of error in sampling are :—

(1) the sample may be contaminated by air;
(2) the sample may not correctly represent the gas;
(3) the sample may change in composition during sampling or during storage before analysis.

1. To avoid inclusion of air in the sample it is necessary to be sure the sample stopcock and all connexions are air-tight. Occasions may arise when there will be a slight suction at the sampling point. In these cases the correct method is to use a pair of aspirators containing a confining agent and connected together by rubber tubing. One of the aspirators is connected to the sampling point by a short length of rubber tubing and a three-way stopcock; then, by alternately drawing gas into this aspirator and venting it through the three-way stopcock, it is possible to purge the line prior to taking a sample without disconnecting the apparatus from the sampling point.

2. When a sample is required from gas under pressure, the sample stopcock should always be opened *for a few seconds* prior to the sampling in order to purge any air or "dead" gas from the line. The length of

purging time will depend upon the capacity of the sampling line. For liquefied gases under pressure, the sample must always be drawn from the liquid phase.

3. The composition of samples may be altered by the release or absorption of certain constituents by the confining liquid. For instance, aspirators which have been used for sampling a gas containing a high percentage of carbon dioxide must not later be used for a gas having a low carbon dioxide content. If a sample must be taken and cannot be tested at once, the sample should be collected in such a way that the confining liquid is *completely* displaced from the one aspirator to the other and the two isolated by means of a screw clip on the connecting rubber tubing. The rate of sampling should be so controlled that the gas sample is collected slowly.

Determination of Carbon Dioxide, Oxygen, Carbon Monoxide, and Unsaturateds.

Sufficient freshly prepared confining liquid (*e.g.*, acidified brine) to fill burette and manifold is placed in the levelling bottle attached to the burette. The pipettes are filled with their respective reagents, which are drawn up to the three-way stopcocks, immediately above the pipettes. A supply of inert gas for sweeping out the combustion furnace is prepared, if necessary, from atmospheric air and stored in a pipette. The measuring burette and manifold are now filled with confining liquid, and the apparatus is ready for use. Alternatively the manifold line may be filled at atmospheric pressure with inert gas.

A convenient quantity of gas is now drawn into the burette and its volume measured at atmospheric pressure. The burette is now connected to the carbon dioxide absorption pipette, and the sample passed repeatedly through the potassium hydroxide solution until no further decrease in volume is observed. The absorption procedure is now repeated with the appropriate reagents, being continued in each case until no further decrease in volume occurs, in order to determine the unsaturateds, oxygen, and carbon monoxide content respectively.

Note : The order of removal of the constituents will vary according to the reagent used for absorption of olefins (see comments on Hofmann's solution).

Before each analysis the manifold is filled either with confining liquid or inert gas. If confining liquid is used, care must be taken to bring the liquid back to the same mark prior to each volume measurement. A further precaution which must always be taken is that sufficient time must be allowed for the draining of the acid water from the walls of the measuring tube. One minute will usually suffice.

Determination of Combustible Components.

After removal of the components as above, combustible gases (hydrogen, methane, ethane, etc) are then estimated by choice of method depending upon the particular combination of gases present. The usual combustion methods are outlined in the following section. When a gas is burned with an excess of oxygen, the amount of gas burned, and in some cases its identity, can be determined from one or more of the following experimental data :—

(i) contraction in volume;
(ii) volume of carbon dioxide produced;
(iii) volume of oxygen consumed.

The volume changes produced by the combustion of hydrogen and the various hydrocarbons may be derived from the equations of combustion and are given in standard works of reference.

Methods of Combustion.

These can be divided into two groups: (1) rapid combustion or explosion; (2) slow combustion. Of the two, the slow combustion is the more accurate. If, however, the gas is to be exploded, in order to obtain the best results it is essential that some idea of the composition be known beforehand. If necessary, a preliminary analysis should be performed.

1. *Explosion Method.* The explosion must be neither too weak nor yet too violent, and the amount of oxygen to be added must be carefully regulated. The usual way of initiating the explosion is by means of a spark across platinum electrodes sealed in a suitable pipette. The spark is produced by a small induction coil or a magneto.

2. *Slow Combustion Method.* Slow combustion is usually carried out over palladized asbestos or over a heated platinum spiral, and various modifications of apparatus are available. The following points should be noted:—

(*a*) If palladized asbestos is used, hydrogen can be estimated by selective combustion at 100° C, and the remaining hydrocarbons can be combusted over the palladized asbestos at 700° C.

(*b*) Apparatus using a heated platinum spiral should be so designed that the gas passes slowly over the filament, which is placed near the gas inlet, so avoiding the formation of an explosive mixture.

(*c*) Oxygen must be present in an excess of at least 10 to 15 per cent. If insufficient oxygen is present, an increase in volume may be recorded, due to the formation of hydrogen and carbon monoxide from methane and ethane instead of water and carbon dioxide.

3. *Fractional Combustion.* In the combustion methods outlined above, the combustible components have been burned together. It is, however, possible to estimate hydrogen and the paraffin hydrocarbons (calculated as methane and ethane) in the presence of each other by fractional combustion, usually employing copper oxide. The latter is heated in a small furnace which can be controlled at the required temperature. At temperatures between 260° and 295° C, hydrogen may be completely oxidized, whereas methane is substantially unaffected. Ethane and higher hydrocarbons are, however, sometimes partially oxidized at such temperatures, and it is therefore necessary, when combusting hydrogen, to determine whether any carbon dioxide has been formed, so that due allowance may be made when calculating the hydrogen concentration. The above assumes that carbon monoxide, if present in the original sample, has been previously removed by chemical absorption, since this gas will be completely oxidized by copper oxide under these conditions.

Hydrocarbons may be completely burned by raising the temperature of

the copper oxide to at least 900° C, or alternatively a second furnace tube containing copper oxide compounded with 1 per cent ferric oxide and maintained at 570° to 600° C may be used.[4]

Sources of Error.

Accurate analysis by absorption methods depends upon careful experimental technique, details of which will vary with the type of apparatus used. The following indicate certain factors to which attention must be given in all cases :—

1. Where any connexions are made with rubber, the capillaries must be glass to glass, and thick-walled rubber tubing should be used, but if possible all rubber joints should be eliminated.
2. The use of single-way stopcocks connecting pipettes to a length of capillary tubing is to be avoided. A manifold made by joining together the requisite number of three-way stopcocks with the right-angle arm joined to the pipette is to be preferred as it allows " dead space " to be eliminated by bringing the reagent almost to the manifold.
3. Stopcocks should be of good quality and should be carefully lubricated. Excess lubricant may cause error if allowed to enter the combustion vessel, while insufficient grease will " streak " and give rise to leakage. Time spent in cleaning and greasing of stopcocks is never wasted.
4. A close record should be kept of the quantities of gas absorbed by each solution, so as to avoid incomplete absorption due to exhausted reagents. Renewal should take place after about 75 per cent of the theoretical absorption or as soon as any marked decrease in rate of gas absorption is experienced. It should be noted also that alkaline pyrogallol and cuprous chloride solutions are liable to evolve carbon monoxide on ageing.
5. In order to avoid physical solution of constituents other than that being chemically removed by the absorbent in question, absorbents should be saturated with the gas under test. This is preferable to the use of nitrogen or other inert gas, since serious errors may be caused due to the occurrences of preferential absorption causing the saturating gas to come out of solution. Further, errors may arise due to nitrogen, or gas differing in composition from the sample under test, being evolved on change of temperature.
6. All glass apparatus should be carefully cleaned with a solution of potassium dichromate in concentrated sulphuric acid.
7. Apparatus, after assembly, should be carefully checked for leaks, and the check repeated periodically.
8. Capillary error should be reduced by flushing with inert gas to displace trapped reactive gas.
9. Gases should not be passed through an absorbent unnecessarily, the number of passes being kept to the minimum consistent with complete removal of the component.
10. The furnace tubes should be packed with copper oxide in the heated region only, and the ends should be packed with silica chips to avoid absorption of carbon dioxide by the cool oxide.

11. Sufficient inert gas should be used for sweeping out the furnace to remove all the carbon dioxide formed; usually three times the space volume is sufficient. Alternatively, products of combustion may be removed by evacuation, using the mercury in the gas burette as a Toepler pump.

12. The readings on the measuring burette are liable to an error due to: (*a*) insufficient time for drainage, and (*b*) parallax. If mercury is used as the confining agent, care must be taken that the burette walls remain properly moistened with water, and that this water is not removed by repeated passage of the gas sample into sulphuric acid absorbing solutions.

13. Unless the platinum filament used for slow combustion is properly made and correctly heated, incomplete combustion is likely and free carbon will be deposited on the sides of the vessel.

References.

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[3] Stone, H. W., and Skavinski, E. R. *Industr. Engng Chem. Anal.*, 1945, **17**, 495.
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THE INSTITUTE OF PETROLEUM.

REPORT OF COUNCIL FOR 1948.

MEMBERSHIP.

Details of membership as at December 31, 1948 :—

	Total Dec. 31, 1947.	Changes during 1948.						Total Dec. 31, 1948.
		New.	Transferred to.	Resigned.	Deceased.	Transferred from.	+ or −.	
Hon. Members	11	—	—	—	—	—	—	11
Hon. Fellows	3	—	—	—	—	—	—	3
Members	705	44	2	113 *	7	9	− 83	622
Fellows	489	44	16	28 *	9	—	+ 23	512
Assoc. Fellows	16	158	7	—	—	—	+165	181
Assoc. Members	767	100	1	138 *	4	12	− 53	714
Students	226	40	—	57 *	—	5	− 22	204
Totals	2217	386	26	336 *	20	26	+ 30	2247
Member-Companies	—	60	—	—	—	—	+ 60	60

* See below.

These figures represent an up-to-date picture of membership, as names of members with whom contact was lost during the war years and with whom, in spite of all efforts, it has proved impossible to re-establish contact, have been eliminated. *This accounts for the high figures in the "resigned" column. Making due allowance for this, there has been a welcome influx of new members.

Member-Companies, a grade introduced at the Annual General Meeting in 1948 to provide a closer link between the Institute and companies associated with the petroleum and its allied industries, appear for the first time.

The number of applications for election as member-companies to date has been somewhat disappointing, but it is confidently anticipated that the number will increase rapidly during 1949 as the advantages to industry of a strong Institute of Petroleum become more generally appreciated.

DEATHS.

Council regrets to record the deaths of the following :

	Class of membership.
A. C. Adams (*Past-President*)	Fellow.
J. C. Brown	Assoc. Member.
A. G. Forbes	Fellow.
W. R. Guy (*Member of Council*)	Fellow.
H. K. Hillier	Member.
F. E. Hunter	Member.

	Class of membership.
H. C. B. Hickling	Member.
G. J. Hancock	Member.
H. C. Ives	Member.
D. H. Jackson	Fellow.
S. Launy	Fellow.
T. G. Madgwick	Fellow.
R. J. Macartney	Fellow.
H. E. Medlicott	Fellow.
T. C. Palmer (*Founder Member*)	Member.
W. H. Park	Member.
W. A. Peters	Assoc. Member.
A. W. H. Phelps	Fellow.
S. A. G. Priestly	Assoc. Member.
B. J. Vavasour	Assoc. Member.

General.

Mr E. A. Evans succeeded Sir Andrew Agnew, C.B.E., as President at the Annual General Meeting in April. Sir Andrew delivered an important address to a distinguished audience of members and guests, on the work of the Petroleum Board during the war.

Mr D. A. Hough was appointed General Secretary of the Institute in September, and Mr G. Sell was appointed Editor.

A new lease for the existing premises at Manson House was negotiated, and in October the Institute took over much needed additional space, providing new Council and committee rooms and improved office accommodation. This has enabled the Library to be reserved for the use of members, and in addition it has been possible to provide canteen facilities for staff lunches and to serve coffee or tea at committee meetings.

Now that it will no longer be necessary to use the Library for committee meetings, Council wish to encourage members to make full use of the Library facilities.

An up-to-date version of the Articles of Association and the By-Laws was printed and supplied to every Corporate Member.

A very successful conference on Modern Applications of Liquid Fuel was held jointly with the Institute of Fuel at Birmingham University by courtesy of the Vice-Chancellor. Council welcomed this opportunity for co-operation with the Institute of Fuel, and arrangements will be made for further joint meetings on suitable occasions.

In August a reception was arranged at the premises of the Institute for the petroleum geologists attending the International Geological Conference. This was well attended.

A final design was approved of a Monogram for the Institute, and further progress was made with the development of a Crest in conjunction with the Royal College of Heralds.

Branches and Students' Section.

A London Branch was inaugurated early in the year, and there is every indication that this Branch will be as successful as the provincial branches, where interest continues to be keen.

The total number of Branch Members, as distinct from Corporate or Student Members associated with the Branches, is 437. The committees

in the branches have done much valuable work in encouraging Branch Members who are suitably qualified to apply for corporate membership.

The Trinidad Branch continues to flourish. Council attaches much importance to foreign branches as a valuable link between members abroad and the parent Institute. Members of the Institute from Abadan and from Australia who have been home on leave during the year have gone back to their respective countries hoping to form new branches. In addition, the formation of a branch in Peru is under investigation.

Council appointed Mr H. E. F. Pracy to maintain liaison between the Branches Committee and overseas branches and members, as a result of which closer touch has been maintained with members overseas.

Members from abroad visiting London will be welcome at Manson House.

Publications.

The high standard of publications by the Institute has been maintained. Volume 34 of the *Journal* with the usual full range of Abstracts and Volume 2 of the *I.P. Review* were both published monthly during the year, the size of the latter being limited only by the restrictions imposed on paper supply by the Board of Trade. The provision of suitable articles for publication in the *I.P. Review* still occasions the Papers Sub-Committee some concern, and members are invited to help in the solution of this problem by submitting articles for this periodical.

It had been hoped to issue *Petroleum Technology 1946* during the year, but the non-receipt of certain essential chapters prevented this. It is expected that the volume will be ready during the first half of 1949, and endeavours are also being made to issue the volume for 1947 during 1949.

The Ninth Edition of *Standard Methods for Testing Petroleum and its Products* was issued in March 1948 and was nearly out of print by the end of the year. *Tables for Measurement of Oil* also became out of print during the year, and a reprint is in hand to fill the needs of the industry.

Research.

The Hydrocarbon Research Group remains active. Satisfactory progress is recorded by both the Hydrocarbon Synthesis Panel and the Spectroscopic Panel. A new panel for the development of Mass Spectrometry has been formed.

The programme of Research Group No. 2 dealing with certain biological aspects related to petroleum has been reviewed and revised to ensure that the work of this Group is integrated within the larger investigation being undertaken by the Medical Research Council in co-operation with various Government bodies. A satisfactory programme has been agreed and work is well in hand.

Engineering.

A revision of the Institute's electrical Code has been almost completed.

Through the various oil companies experiments are being put in hand by the Engineering Committee to determine the extent of "dangerous

acids " as defined in the Code. So far as the Committee is aware there is very little data on this subject, and the information, when collected, should be invaluable to the industry in general. Such data could then be used as a basis for compiling safety codes in the industry. It will also form the basis of the Guide to Safety Regulations which the Engineering Committee proposes to draw up and this work will be the main subject for the Committee during the ensuing year.

Standardization.

Standardization Committee, through its various Sub-Committees, Panels, and Working Groups, has continued actively throughout the year its work of improving existing standard testing methods of the Institute, and of standardizing new methods where required.

Close co-operation has been maintained with the American Society for Testing Materials and with the British Standards Institution. The advantages of international standardization have been kept in mind, and discussions have taken place with representatives of other national associations interested in standardization.

Awards.

The Redwood Medal was awarded to Mr H. S. Gibson, C.B.E., who delivered an address on " The Production of Oil from the Fields of South-western Iran " to a crowded meeting of members and guests.

The following scholarships were awarded :—

Mr P. W. Taylor, Royal School of Mines;
Mr D. Hammerton, Birmingham University.

Benevolent Fund.

During the past year, subscriptions have totalled £204. Current assets amount to £2640. A substantial grant was made to the widow of a member towards the education of her young son.

It is unnecessary to stress the importance which Council attaches to this fund, and it is hoped that generous support will be forthcoming to enable substantial assets to be built up from which help can be provided in all cases of need.

Finance.

There will again be a deficit in 1948. The Finance Committee has been fully alive to the problem and has made investigations as to the most effective and equitable means of accomplishing a balanced budget.

Expenditure during the year increased substantially, due to increased rent following a renewal of the Institute's lease, with additional office space at Manson House, additional staff required for expanding activities, increased printing and office administration costs, etc.

It became increasingly clear that the wide gap between income and expenditure could be bridged only by a substantial increase in revenue.

The Finance Committee, in conjunction with other Council Committees such as the House and Publications committees, gave full consideration to the possibilities of effecting economies, but the view of Council was that the services provided by the Institute to its members and to industry should not be curtailed when the industry itself was expanding in the U.K. In these circumstances it was obvious that the budget gap could be closed only very slightly by economies in expenditure.

It is anticipated that the support which will be forthcoming from Member-Companies will go a long way towards bridging the gap, but the increased cost of providing the Institute's publications (the *Journal* and the *I.P. Review*) to Corporate Members would seem to justify an increase in the membership subscription rates which have remained unaltered for many years, although the facilities provided for members have very considerably increased. This matter is receiving the close attention of the Finance Committee.

Education Committee.

In conjunction with the City and Guilds of London Institute, which will conduct the examinations, the Education Committee has completed a part-time scheme for the technological training to degree standard of petroleum company employees, and attendances at classes covering the subjects of the scheme have begun at Llandarcy. At its next meeting in April the Committee will consider what further activities are desirable.

Acknowledgment.

Council wishes to record its appreciation of the services of the staff of the Institute, and to emphasize again the debt which the Institute owes to the petroleum companies for allowing their staffs to give so much time to the affairs of the Institute and to individual members for all the help they have given in the past year.

By Order of the Council,
C. Chilvers, Hon. Secretary.

THE INSTITU

(*A Company limited by Guara*

BALANCE SHEET

CAPITAL AND RESERVES.

	£	s.	d.	£	s.	d.
Capital of the Institute under Bye-Laws 36, 44, and 45 :—						
Life Membership Fund—	£	s.	d.			
As at December 31, 1947	899	4	0			
Add Subscriptions during year	20	0	0			
				919	4	0
Entrance and Transfer Fees—						
As at December 31, 1947	4771	17	9			
Add Receipts during 1948—						
Entrance Fees	449	8	0			
Transfer Fees	14	14	0			
				5235	19	9
Profit on Sale of Investments—						
As at December 31, 1947	356	10	11			
Less Net Loss during 1948	98	11	7			
				257	19	4
Donations—						
As at December 31, 1947				326	5	0
					6739	8 1
T. C. J. Burgess Prize Fund					5	0 0
General Reserve (previously War Contingencies Reserve)					1702	0 11
Revenue Account :—						
As at December 31, 1947				3908	2	9
Less Deficit for the year as per attached account				1310	9	5
					2597	13 4
					11,044	2 4
Subscriptions Received in Advance :—						
Members' Subscriptions for 1949				424	4	0
Member-Company Subscriptions for 1949				1005	7	6
Journal Subscriptions for 1949				873	0	6
Subscriptions for 1950 and 1951				38	18	10
					2341	10 10
Current Liabilities :—						
Sundry Creditors and Accrued Charges				1236	4	6
World Petroleum Congress				273	8	6
					1509	13 0
					£14,895	6 2

Approved by Council :
E. A. EVANS, President.
G. H. COXON, Hon. Treasurer.

REPORT OF THE AUDITORS TO THE MEMBERS

We have obtained all the information and explanations which to the best of our knowledge
been kept by the Institute so far as appears from our examination of those books. We
books of account. In our opinion and to the best of our information and according to the exp
manner so required and the Balance Sheet gives a true and fair view of the state of the Insti
or the year ended on that date.

3, FREDERICK'S PLACE,
OLD JEWRY, LONDON, E.C. 2.
April 8, 1949.

PETROLEUM.

not having a Share Capital.)

DECEMBER 31, 1948.

					1947
FIXED ASSETS.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£
estments :—					
n Account of Capital, at cost—					
£525 0 0 3% Savings Bonds, 1955/65	525 0 0				
867 8 6 2¾% Bristol Corporation Redeemable Stock, 1955/65	845 17 7				
150 0 0 3% Smethwick Corporation Redeemable Stock, 1956/58	151 4 9				
150 0 0 3% Luton Corporation Redeemable Stock, 1958	151 6 7				
806 8 3 3% Manchester Corporation Redeemable Consolidated Stock, 1958	845 17 7				
600 0 0 3% Bristol Corporation Redeemable Stock, 1958/63	597 7 3				
664 6 6 3% London County Consolidated Stock, 1920	481 10 6				
400 0 0 3% Metropolitan Water Board "A" Stock, 1963	346 10 7				
150 0 0 5% Wandsworth & District Gas Co. Debenture Stock	154 8 6				
156 9 8 3% British Transport Guaranteed Stock 1978/88	105 4 9				
461 0 0 2½% Funding Loan, 1956/61	461 15 6				
500 0 0 2½% Defence Bonds	500 0 0				
(Market Value at December 31, 1948, £5524.)	5166 3 7				*5196*
ash awaiting Investment on Deposit with Post Office Savings Bank	1573 4 6				*1158*
			6739 8 1		
n Account of Revenue, at cost—					
£475 0 0 3% Savings Bonds, 1955/65	475 0 0				
2000 0 0 3% Savings Bonds, 1960/70	2000 0 0				
			2475 0 0		*4175*
(Market Value at December 31, 1948, £2566.)					
ce and Library Furniture at cost, less amounts written off :—					
s at December 31, 1947	193 12 3				*194*
dd Additions during 1948	679 13 2				
			873 5 5		
			10,087 13 6		*10,723*
rrent Assets :—					
undry Debtors and payments in advance, including Income Tax recoverable to date	1415 17 11				*1743*
ubscriptions in arrear (not valued)	—				
ash at Bank on Current Account and in hand	1221 13 2				*854*
ash on Deposit with Post Office Savings Bank—					
General Account	1896 13 1				*2227*
World Petroleum Congress	273 8 6				*267*
			4807 12 8		
			£14,895 6 2		*£15,814*

E INSTITUTE OF PETROLEUM.

ef were necessary for the purposes of our audit. In our opinion proper books of account have mined the above Balance Sheet and annexed Revenue Account which are in agreement with the s given us the accounts give the information required by the Companies Act, 1948, in the irs as at December 31, 1948, and the Revenue Account gives a true and fair view of the result

PRICE, WATERHOUSE & Co.,
Chartered Accountants.
Auditors.

THE INSTITUTE

REVENUE ACCOUNT FOR THE

	£ s. d.	£ s. d.	1947 £
To Administrative Expenses :—			
Staff Salaries and National Insurance	5109 2 8		*4687*
Printing and Stationery	989 1 6		*664*
General Postages	118 2 4		*117*
Telephones, Cables and Travelling Expenses	120 6 9		*105*
Audit Fee	73 10 0		*73*
Legal Fees	106 10 0		*46*
General Expenses	659 7 6		*413*
		7176 0 9	
„ **Establishment Expenses :—**			
Rent, less amounts recovered	835 3 8		*375*
Cleaning, Lighting and Lift Expenses	236 19 3		*248*
		1072 2 11	
„ **Publications Expenses :—**			
Institute Journal Expenses	3948 15 0		*4083*
I.P. Review Expenses	1329 9 2		*1637*
Abstractors' Fees	240 17 6		*284*
Standard Methods	643 16 5		*562*
Modern Petroleum Technology	42 10 9		*95*
Reviews of Petroleum Technology	63 12 10		*1088*
Other Publications	3 18 0		*245*
		6272 19 8	
„ **Dispatch Expenses**		588 9 11	*593*
„ **Meetings :—**			
Hire of Hall, Pre-Prints, Reporting, etc.		439 18 6	*295*
„ **Branches and Sections :—**			
Scottish Branch	42 3 0		
Northern Branch	108 3 0		
South Wales Branch	38 15 0		
London Branch	57 10 6		
Stanlow Branch	47 18 6		
Trinidad Branch	40 3 6		*194*
		334 13 6	
Sundries :—			
Library Expenses	97 7 11		
Subscriptions to Societies	61 19 6		
Scholarship Awards	100 0 0		
Honoraria	375 0 0		
		634 7 5	*645*
		£16,518 12 8	*£16,452*

OF PETROLEUM.

YEAR ENDED DECEMBER 31, 1948.

							1947
				£	s.	d.	£
By	Members' Subscriptions received for 1948			5383	6	3	4822
„	Members' Subscriptions in Arrear, received during year			94	10	0	119
„	Special Subscription			20	0	0	20
„	Publications Receipts for 1948 :—	£	s. d.				
	Advertising	3233	5 3				
	Journal, I.P. Review, and Abstracts	1960	2 2				
	Other Publications	4140	8 11				9017
				9333	16	4	
„	Interest and Dividends received (Gross)			344	0	2	371
„	Amounts recoverable from Branches (including Refund £25 from South Wales)			32	10	6	50
„	Balance, being Deficit for the Year carried to Balance Sheet			1310	9	5	2052
				£16,518	12	8	£16,452

CADMAN MEMORIAL FUND.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1948.

	£ s. d.		£ s. d.
To Balance at 31st December, 1948 :—		**By Balance at December 31, 1947**	2972 6 7
Cash at Bank on Current Account	230 1 1	„ **Interest received and tax recoverable during year**	81 18 0
£2730 3% Savings Bonds, 1965/75 (Market Value 31st December, 1948, £2812)	2730 0 0		
Income Tax recoverable	55 5 6		
Sundry Debtor :—			
Institute of Petroleum	38 18 0		
	3054 4 7		
	£3054 4 7		£3054 4 7

We have examined the above Income and Expenditure Account with the books and vouchers of the Fund, and find it to be in accordance therewith. We have verified the cash with Bankers to be in accordance with the balance on December 31, 1948.

3, FREDERICK'S PLACE,
OLD JEWRY, LONDON, E.C. 2.
April 8, 1949.

PRICE, WATERHOUSE & Co.,
Chartered Accountants.
Auditors.

HYDROCARBON RESEARCH GROUP.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1948.

	£ s. d.	£ s. d.		£ s. d.
To Grants :—			**By Balance at December 31, 1947**	1111 7 7
University of Cambridge	625 0 0		„ **Voluntary Contributions received from Members of the Group during the year**	5000 0 0
University of Oxford	1000 0 0			
University of Birmingham	1382 9 8			
Bedford College	750 0 0			
Queen Mary College	576 16 8			
		4334 6 4		
„ **Honoraria**		787 10 0		
„ **General Expenses**		73 5 6		
„ **Wages**		159 16 7		
„ **Balance at December 31, 1948, represented by cash at Westminster Bank, Limited**	£916 5 9			
Less Sundry Creditors, Institute of Petroleum	159 16 7			
		756 9 2		
		£6111 7 7		£6111 7 7

We have examined the above Income and Expenditure Account with the books and vouchers of the Fund, and find it to be in accordance therewith. We have verified the cash with Bankers to be in accordance with the balance on December 31, 1948.

We have examined the above Income and Expenditure Account with the books and vouchers of the Fund, and find it to be in accordance therewith. We have verified the cash with Bankers to be in accordance with the balance on December 31, 1948.

B B

CARCINOGENICITY RESEARCH FUND.

INCOME AND EXPENDITURE ACCOUNT FOR THE PERIOD ENDED DECEMBER 31, 1948.

	£	s.	d.		£	s.	d.
To Balance at December 31, 1948, represented by Cash at Westminster Bank, Ltd.. .	2000	0	0	By Cash received from the Petroleum Board (during 1947) on account of research at Birmingham University	2000	0	0
	£2000	0	0		£2000	0	0

We have examined the above Income and Expenditure Account with the books and vouchers of the Fund, and find it to be in accordance therewith. We have verified the cash with Bankers to be in accordance with the balance on December 31, 1948.

3, FREDERICK'S PLACE,
OLD JEWRY, LONDON, E.C. 2.
April 8, 1949.

PRICE, WATERHOUSE & CO.,
Chartered Accountants.
Auditors.

BENEVOLENT FUND.

Receipts and Payments Account for the Year ended December 31, 1948.

Receipts.

	£ s. d.	£ s. d.	1947 £
Balance at December 31, 1947		2481 8 2	*2286*
Receipts during 1948 :—			
Subscriptions and Donations	204 10 2		*76*
Interest, gross	56 15 0		*48*
		261 5 2	
Profit on Redemption of 3% Local Loans		—	*71*
		£2742 13 4	*£2481*

Payments.

	£ s. d.	1947 £
Grant paid	100 0 0	—
Balance at December 31, 1948	2642 13 4	*2481*
	£2742 13 4	*£2481*

The Balance at December 31, 1948, was held as follows :—

	£ s. d.
Cash at Bank on Current Account	435 15 4
£550 3% Defence Bonds *	550 0 0
£1550 2½% Defence Bonds *	1550 0 0
Income Tax recoverable	6 1 6
Sundry Debtor :—	
Institute of Petroleum	100 16 6
	£2642 13 4

* (Market value at December 31, 1948, £2100.)

We have examined the above Receipts and Payments Account with the books and vouchers of the Fund and find it to be in accordance therewith. We have verified the Investments and the Balances with Bankers and The Institute of Petroleum comprising the Balance on December 31, 1948.

3, Frederick's Place,
Old Jewry, London, E.C. 2.
April 8, 1949.

Price, Waterhouse & Co.,
Chartered Accountants.
Auditors.

THE INSTITUTE OF PETROLEUM.

THIRTY-SIXTH ANNUAL GENERAL MEETING.

THE Thirty-Sixth Annual General Meeting of the Institute of Petroleum was held in the lecture hall of the Royal Society of Arts, John Adam Street, Adelphi, London, W.C.2, on Wednesday, April 27, 1949. The President, MR E. A. EVANS, occupied the Chair.

THE GENERAL SECRETARY (D. A. Hough) read the notice convening the meeting.

The Minutes of the adjourned Thirty-Fourth Annual General Meeting (held on June 9, 1948), the Thirty-Fifth Annual General Meeting (held on April 30, 1948), and the adjourned Thirty-Fifth Annual General Meeting (held on October 14, 1948), were read, confirmed, and signed.

OFFICERS FOR THE SESSION 1949–50.

President.

MR C. CHILVERS (Hon. Secretary): I would like to propose that Mr E. A. Evans be re-elected President for the year 1949–50.

I do not think this is really the time to elaborate on the great distinction with which Mr Evans has carried out his duties during the year that has passed; but I think you should all know that it is by the unanimous nomination of Council that Mr Evans' name is put forward at this meeting for re-election to the presidency for the coming year.

MR H. HYAMS (Vice-President): May I formally second the proposal and add that we all appreciate what a debt we owe to Mr Evans for the way in which he has led the Council in the conduct of the affairs of the Institute during the past year.

(The proposal was carried unanimously, and the President briefly responded.)

Vice-Presidents.

The following were nominated for election as vice-presidents for the year; and on the motion of Mr E. J. Sturgess, seconded by Mr D. L. Samuel, they were unanimously elected :—

M. A. L. Banks	H. Hyams
E. J. Dunstan	J. S. Parker
E. B. Evans	C. A. P. Southwell

Members of Council.

THE GENERAL SECRETARY announced that the following had been elected by ballot to fill the seven vacancies on the Council :—

V. Biske	J. A. Oriel
C. D. Brewer	R. B. Southall
F. L. Garton	H. C. Tett
H. S. Gibson	

Hon. Treasurer.

MR E. THORNTON : I have great pleasure in proposing that Mr G. H. Coxon be re-elected Hon. Treasurer.

MR F. L. GARTON : I have pleasure in seconding.

(Mr Coxon was unanimously re-elected.)

Hon. Secretary.

MR F. L. GARTON : I should like to propose the re-election of Mr C. Chilvers as Hon. Secretary.

(The motion was seconded by Mr R. J. Bressey, and carried unanimously.)

Ex-Officio Members of Council.

It was announced by the General Secretary that the following had been nominated to serve as ex-officio Members of Council for 1949–50; and on the motion of Mr E. Thornton, seconded by Mr Hall, they were elected :—

A. J. Goodfellow N. E. F. Hitchcock	*London Branch*
T. W. Ranson	*Northern Branch*
E. J. Horley	*South Wales Branch*
A. Fleming	*Scottish Branch*
J. G. Hancock	*Stanlow Branch*

MEMBERS ELECTED AND TRANSFERRED.

Lists of Honorary Members, Honorary Fellows, Members, Fellows, Associate Members, Associate Fellows, and Students elected or transferred during the year 1948 were laid on the table.

REPORT OF COUNCIL, 1948.

THE PRESIDENT, proposing the adoption of the Annual Report of Council for the year ending December 31, 1948, said :—

It is my pleasure first of all to refer to three members who have served Council for a number of years with great distinction, and whose loss from Council we do in a measure deplore. They are Mr A. Beeby Thompson, Mr A. T. Beazley, and Mr R. R. Tweed. Those are names that have been known in the petroleum industry for many years. But we have to recognize that we must have new members serving on Council in order to maintain continuity. Although we miss the three distinguished petroleum technologists I have mentioned, we offer a welcome to the new members of Council.

A great deal of activity has been displayed by Mr A. J. Goodfellow and Mr N. E. F. Hitchcock in the formulation of the London Branch during the past year. They have worked with indefatigable energy; I am sure we should all like to offer our thanks to them for their work; and I assure them that we shall welcome them as ex-officio members of Council.

Amongst the new things in life which we have enjoyed and are going to enjoy further there is first the Monogram, and secondly the Crest, of

the Institute. We feel we have almost been elevated to the aristocracy by being granted the Crest. It is also useful to have the Monogram, because it can figure on all our documents; it is a sort of "trade mark" and will distinguish us from other organizations, which I think is all to the good, particularly when we are referring to our standard methods. The Crest will be used in a more limited way. Each has its applications.

The question of finance I must leave to Mr Coxon, who will, I feel sure, deal with it with his usual thoroughness.

We ought to express a word of appreciation to the branches for the ever-increasing work they are doing and for the hospitality they so frequently extend; I would mention particularly the Branch Committees.

I should also like to make special mention of our Member-Companies. At first there was a little reluctance to respond to our invitation to them to join us; there always is. One company waits to see what another company is doing, but I am glad to say that a large number have joined us, some of them with great generosity.

Lastly, I would draw your attention to the fact that it has been decided to hold a World Petroleum Congress in Holland in 1951. You may think that that is a long time ahead; but these things require a lot of organizing. Whilst we are thinking of 1951, I would remind you that the Festival of Britain will be held in that year and that we may be called upon to exhibit our strength in some way or another then.

I would like to propose from the Chair the adoption of the Annual Report.

(The motion was seconded by Mr Hall, and carried.)

Finance.

Mr G. H. Coxon (Hon. Treasurer): The finance of the Institute is a problem which has been disturbing many of us for a long time. The position to-day is that, on account of the expansion of the Institute and the taking on of new offices, our income has not been keeping pace with our expenditure. We have known that for quite a long time; in 1947 we had a deficit of £2000, but in 1948, despite the growth of our work, we were only £1300 down. However, in 1949 we shall have a much larger expenditure on the extended offices, and have increased our staff to cope with our increased activities.

I, for one, do not despair of this Institute finding the necessary finance, so long as the members of the Institute and the Council are giving the service to the industry we are expected to give. Our responsibility rests upon ourselves. What is it that we are trying to do, and are we doing it? I think we are, and I think we have still more scope for expanding our activities to better the industry as a whole. I would like the Institute to get into the position where the Government Departments ask us what to do in the various phases of the industry, so that we become an even more important body. That should be the aim.

I do not think I have any particular point to make on the Balance Sheet, copies of which are before you, except to say that we have about £4000 in reserve.

(On the motion of Dr. F. Morton, seconded by Mr A. J. Goodfellow, the Balance Sheet and Accounts for 1948 were adopted.)

Appointment of Auditors.

Mr H. Hyams: I desire to move that we again appoint Messrs Price, Waterhouse & Company as Auditors for the year 1949–50. I think they ought to be complimented on getting our accounts out in good time for presentation at the Annual General Meeting held in the statutory period of the first four months of the year. It looks as though, with the aid of this firm, we have left behind us the necessity to adjourn the Annual General Meeting and to deal with the accounts separately at an adjourned meeting.

In view of their good service to us in the past year, I propose that Messrs Price, Waterhouse & Company be appointed auditors for 1949–50.

Mr A. T. Wilford seconded.

The President: It is my understanding that, according to the Finance Act, 1948, we shall not be able in future to elect another auditor without prior notice. So that if it should be the wish of anybody to elect new auditors, prior notice must be given before the Annual General Meeting.

(Messrs Price, Waterhouse & Company were appointed Auditors for 1949–50.)

Membership Subscriptions.

Mr H. Hyams: In accordance with the By-Laws, any intention to amend a By-Law has to be notified to the members at an Ordinary Meeting in advance of the consideration of the proposed alteration at an Annual General Meeting or a Special General Meeting.

The Council desires, therefore, to give preliminary notice that, at a Special General Meeting to be called, it is intended to alter the particular By-Law which applies to the subscription rates for Corporate Members of the Institute. For the reasons which have already been given by Mr Coxon, we are not operating on an even keel financially at the moment. Some of the additional income needed, we feel, must come from the members themselves.

The intention is, therefore, to amend the subscription rates for Corporate Members (Fellows and Associate Fellows, Members and Associate Members). The Members and Fellows will be asked to pay £4 4*s*. per annum instead of £3 3*s*., and the Associate Members and Associate Fellows will be asked to pay £3 3*s*. instead of £2 12*s*. 6*d*. It is estimated that that increase will give us an additional income of the order of £1500 or £1600 a year, which will go towards meeting the deficit which we expect to have to meet for the year 1949.

Votes of Thanks.

The President: In view of the financial position of the Institute a special word of thanks is due to certain people who have done an enormous amount of thinking and work. Mr Coxon especially has been extremely active in this particular connexion, and Mr Hyams and Mr Oriel have done yeoman service; and there are others. You may wonder why Mr Hyams speaks with such authority as he does on finance matters. I would remind those who are not Members of Council that he is now Chair-

man of the Finance Committee. Mr Chilvers also carries a great load of our work, and I think it is proper that at this Annual Meeting, even if it is repeated year by year, we should give our thanks to those gentlemen for their special services. And we must not forget the work of our permanent officers and their colleagues at Manson House. (Applause.)

MR CHILVERS: Before this meeting closes, I think that all present would like to express thanks to you, Mr President, for having presided, and we should like also to say how much we appreciate the work you have done during the year that has passed. Those of us who are on the Council, who are in close touch with the business affairs of the Institute, know the time, the care, and the diligence you have devoted to the work during your term of office. I can assure all members that Mr Evans takes the work of his office extremely seriously; and when the time comes for him to relinquish it I am quite sure we shall have occasion to express our appreciation a little more formally than is perhaps necessary this afternoon. I do assure you, Sir, that we appreciate very much what you are doing for the Institute, and we hope that your new term of office will be as successful as the first. (Applause.)

PRESIDENTIAL ADDRESS.

THE PRESIDENT delivered his presidential address, as follows:—

PIONEERS.

By ELLIOTT A. EVANS (President).

STRENGTHENED by a pride of ancestry we can afford to be magnanimous and revalue some of the achievements of the pioneer adventurers who have bequeathed to us such a heritage. Through their endeavour, the petroleum industry need not fear comparisons. The industry has resisted assimilation, has retained its own traditions, and has become a bulwark of order. The pioneers throughout the years of progress have depended on no man's favour; they have just followed the line of their own imagination. This isolation made them self-reliant and often individualistic. At times these men have made great sacrifices in charting the great fields of human knowledge. Pioneers are the preservers of progress. Their effectiveness was due to their acts of imagination when they saw the potentiality while it was still unverified. Simple though their achievements may appear in later days, a little more reshaping, and a little less destruction, will often reveal an unexpected luxuriance.

One of the greatest links between antiquity and modern civilization is the marvellous petroleum springs at Baku, famous 2500 years ago, and still possessing a challenging appeal. For ages this rich field for romance attracted the surrounding nations to join in the benefits of the oil resources. The Eternal Fire of the Apsheron Peninsula became an object of devotion during the Zoroastrian period about 600 B.C. Remnants of the ancient fire-worshippers later pursued their sacred rites in South-east Persia, and large numbers of them fled to the island of Ormuz, and thence to India to give rise to the Parsees of Bombay. Even as late as the twelfth century

pilgrimages were made to Baku. By the thirteenth century oil was taken away to burn, and to anoint camels against mange. Baku and its natural naphtha springs, however, became a source of discord between the Persian shahs and the Armenian emperors. The primitive instinct of possession continued to dominate the area which led to the annexation of Baku in 1723 by Peter the Great, who gave special instructions to extract the oil and to export it. From then onward there developed a realistic movement. By 1819 the output had reached 4000 tons. In 1824 the Hon George Keppel drew special attention to the differences between the black and white naphtha, but it was not until 1861 that a refinery was erected.

In the United States of America things had also been happening with a persistence and a quiet force. The Indians had dug wells to obtain oil which they called Seneca oil. In 1826 Hildreth suggested that the oil should be used as an illuminant instead of sperm oil. Twenty years later Gesner made an illuminating oil from coal by distillation, in Prince Edward Island, which he called " kerosene." Kier immediately conceived the idea that petroleum could be converted into a better illuminant if it were distilled. His knowledge of combustion suggested to him that a lamp fitted with a glass chimney would give a much cleaner flame. Kier, with commercial acumen, made the labels on his bottles of oil as attractive as possible, and showed a derrick on them. Bissell was attracted by the derricks, and thought it might be possible to bore for petroleum. Bissell entrusted the boring of a well to Drake, who in 1859 struck oil.

At this stage of our history we must pause to pay tribute to our own pioneer, James Young, who in 1850 commenced to distil oil in the United Kingdom.

Competition was clearly and unmistakably showing on the horizon when Herbert Barry made the bald announcement in 1870 that the quality of Russian oil was equal, or superior, to that obtained from America. However true the statement might have been, it was a fact that the American oil had gained a foothold in the European markets. Quite apart from American commercial ability, much of the commercial disparity could be traced to the lack of railways in Russia, the freezing of the Volga in winter, and to tribal insurrections; and maybe because the Russian oil industry had been nationalized until 1872 ! There was a time when it was cheaper for the merchants in the Upper Volga, and indeed Tiflis, to get their oil from America than from the Caspian. For years America controlled the petroleum market of Russia, which was mainly due to the poor transport from the Caspian.

Then the dynamic Ludwig Nobel entered the oil industry of Baku in 1875. Ludwig, the engineer and financier, had the able co-operation of his brothers Robert, an engineer, and Alfred, a chemist. Fortunately, they were very rich men when they entered the industry, so they were able to finance their own projects. First, they had to build watch-houses against the Tartars, then they constructed a pipeline because of the theft of barrels. After that they commenced to build ships, but owing to the tempestuous nature of the Caspian Sea they had to introduce separate compartments to their ships. The first such ship appeared in 1879. As the railway managements would not assist, they made their own tank-cars and built oil-sidings. This enabled the oil merchants to collect their produce at the railheads,

but they had to pay cash. Throughout their great work they were assailed by the Pan-Slavist Press because they were foreigners. However, facts chant their own praise.

When the Nobels started, an English diplomat passed through the Baku district but failed to see anything of interest. Professor Tyndall, on the other hand, described the Baku oil in 1884 as the "new wonder of the world," and the Rothschilds invested nearly £2 million in Baku between 1884 and 1887.

Progressive ideas soon encouraged Russia to step up the flash point of its burning oil to 30° C, which led to a rapid increase in sales in Germany. The importers in England declared that the American oil was becoming worse every year. So, Boverton Redwood, chemist to the London Petroleum Association, instituted tests in about 1880 with some refined petroleum of Nobel's brand. He reported that the colour and odour of the oil compared favourably with the oil from America, but the flash point was 87° F (Abel test), which was higher than the American, and that the American oil was inferior to the Russian oil in the size of flame after some hours burning. The lubricating oil was said to eclipse the American, as it was more viscous and free from a tendency to freeze and oxidize. Russian lubricating oil increased in popularity in many countries, especially in France. By this time Russian oil was being exported to be worked up into lubricants. Doubtless the price which was charged militated against American competition.

Original Lubricants.

The original lubricants were the animal fats, vegetable oils, and fish oil, which remained unchallenged until late in the nineteenth century. As they were naturally occurring, comparatively little attention was paid to them beyond simple processes of purification. Because the demands upon them as lubricants were of a mean order, no critical examination was considered necessary. With the advent of the steam-engine and subsequent machinery, a little more thought was necessarily given to the lubricant. Clearly, a scientific selection was impossible, so it is reasonable to suppose that selection was based upon simple observations such as appearance, freedom from gum formation, and cost. It is easy to believe this supposition when we read that sperm oil became to be regarded as the very best, but owing to its high price its use was limited. Other oils which were cheaper were said to have little lubricating power. In those days changes were necessarily few, consequently a change from olive to rape in 1879 was a realistic movement. Obviously, the significance of film strength was not realized, but it was observed that rape oil had some advantageous property for railway-engine lubrication.[1] Castor oil had achieved no greater credit than being considered a moderately good lubricant for heavy bearings, whereas, perhaps surprisingly, porpoise-jaw oil had already established itself as *the* oil for watches.

Grease was known and used, but not as we know it now. The term "grease" was usually restricted to those soft fats in the tissues of animals, which are solid or nearly so at temperatures not greatly exceeding that of the living animal. So when soap greases were introduced, a distinction

became necessary. As these greases were made from tallow or palm oil rendered alkaline with soda or lime-water, they were called "hard greases."[2] The hard greases became important, because there was a decided tendency to displace oils by them.

The needs of life and circumstance are the constant spur to nomenclature. It therefore becomes interesting to note that elaine oil, so called by Chevreul, or oleine, was the light oil obtained from tallow or other hard fats by pressure or heat, leaving the solid stearine. Oleine has lost its original meaning and is now the commercial name for liquid fatty acids. When oleine was extracted from olive oil the solid left behind was called margarine. Margarine was then apparently the solid fat from vegetable oils.

The expansion of the sales of fatty oils, and the enrichment of the vendor, were followed extensively by adulteration. It is not suggested that adulteration arose out of the sales of fatty oils. The passing of the Coffee Act in 1718 was evidence of a prior art. The first real attempt to cope with adulteration occurred in 1875, when the Sale of Food and Drug Act became law. Although Mege Mouries obtained his patent for margarine in 1869, it was found to be necessary to have on the Statute Book in 1887 the Margarine Act. Thus it became the chief business of the analyst to interest himself in generalizations of such a sort as leads with tolerable straightness to the determination of purity and the detection of adulteration. Chateau,[3] in 1864, described how the job was tackled. It was little more than the register of colour reactions with such things as chloride of zinc, sulphuric acid, bichloride of tin, etc. Of course, some colour tests, *e.g.*, Liebermann–Storch reaction for rosin and the Halphen test for cottonseed, still remain. Nickels,[4] in 1880, regarded these elementary practices distrustfully and proceeded to suggest a digression. He suggested that mixtures of olive or Gallipoli oil with cottonseed could be detected by the spectroscope. He stated that olive as examined by a Browning "direct-vision" or pocket spectroscope presents a deep shadowing, or cutting out of the blue and violet ray, with a fine almost indistinct line in the green, and a strong deep band in the red. Refined cottonseed gives exactly the same appearance in the blue and violet, whereas the green and red are continuous. Another diversion which can only be treated with historic respect relates to the electrical conductivity of oils. Rousseau found that oils are good conductors of electricity, excepting olive which has about 1/700th the conductivity of other oils. So, he devised an instrument called a "diagometer." F. S. Pease found mineral oils to be good conductors also!

Solid lubricants were considered indispensable for certain conditions, *e.g.*, wood on wood. They were usually incorporated with grease for slow-moving machinery, and with asbestos in packing for piston-rods and valve-stems of steam machinery. The two principal ones were graphite and soapstone, now known as talc. I do not know when they were first used, but graphite was mentioned by Rennie in 1829 in *Philosophical Transactions*. Sulphur and white lead were known, but little used.

Instincts or memories which are the shrines of prejudice are difficult to dislodge. Lubrication could no longer be based upon standards of taste, but upon mechanical and scientific standards. The tendency during the growth of the mechanical age was more and more visibly towards the

FIG. 1.

SIR W. H. BAILEY'S PENDULUM TESTER.

[*To face p.* 382.

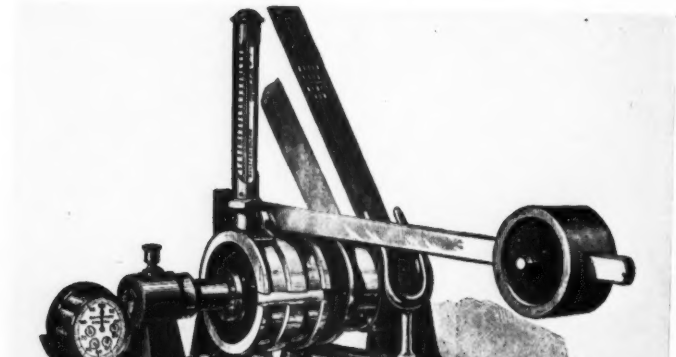

FIG. 2.

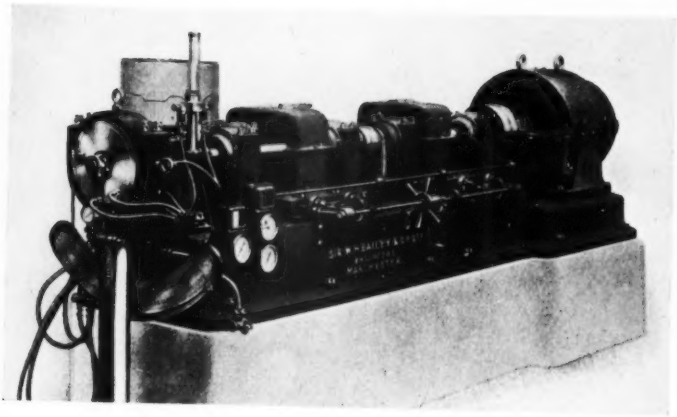

FIG. 3.

THE ADMIRALTY PATTERN OF BAILEY'S "THURSTON" OIL TESTER.

purified material. Of course, it was difficult at first to displace the fatty oils by petroleum products, but gradually the battle was won—not wholly, but in great part, because fatty oils are still used and valued. Mineral oil being a distilled substance had a pleasing appearance, and as it did not contain oxygen nor had any inclination to absorb it, except in insignificant amount, judgment was in its favour. The burden of proof was directed to mechanical tests.

Mechanical Tests.

The early mechanical tests were very simple, yet the principles have remained with us even to the present day. The friction test used in Manchester about 1870 consisted of a friction drum upon which oil was placed. A heavy weight, raised by means of a winch, was allowed to drop several feet. This imparted considerable velocity to the drum; the difference in the number of the revolutions of the drum indicated the value of the lubricant. It was discontinued because its indications were uncertain.

W. H. Bailey of Manchester designed a pendulum tester (Fig. 1) about 1873 for testing oils which will not be subjected to heavy pressures, such as the conditions under which oils will be used for clocks and watches and light spindles. This consists of a pendulum to which is attached a link, which imparts a reciprocating motion to a small piece of brass. The test is made by placing one drop of oil on the surface of the brass and noticing how many times different oils will permit the pendulum to vibrate without stopping. To show the exaggerated position to which mechanical testing developed it is of interest to see two machines (Figs. 2 and 3) which came into use subsequently.

Prices Candle Company showed their dislike for individual tests by testing oils on several thousand spindles turned exclusively by one steam-engine. Diagrams of the power were taken four times daily. Similar methods were used even in this century as a selling aid.

Looking back these events look like fictional portraits of science. But, if we could carry on the narrative to its logical conclusion we would see what great services had been rendered in those early days. The paths which may have been marked by milestones of mistakes only need reshaping, not destruction. Since then, we have graduated from a culinary art to a science. Yet, however dazzling the ingenuity which may have been displayed in bringing petroleum to its present level, it may require some vigorous all-in stuff to make us look far ahead into the future. So, with a memory of the past, we can pass to an anticipation of the future.

Synthetic Lubricants.

Considerable though the supplies of natural petroleum may be, we must possess a flexibility of imagination to keep us from hiding behind the smoke screen of security. It may not always be possible, either through economic or political reasons, to subsist entirely upon Nature's gifts, which after all are not equally distributed throughout the world. To meet the impact of adverse conditions it is necessary to prepare in advance, by research, synthetic alternatives. The hugely expanding possibilities of synthetic chemistry have hardly been visioned yet. Although the swift advance of technology has for a moment run ahead of economics, whose progress must

be gradual rather than revolutionary, it is still necessary to draw upon the findings of workers in pure science and chemical engineering if we are to carry the burden of responsibility to the whole people by translating scientific abstractions into materials of everyday life.

Synthetic petroleum has long engaged the minds of many scientists. In our own Institute we well remember the work of Professor Nash, whose untimely death occurred during his Presidency. Passing to modern procedure, our thoughts go to the Fischer–Tropsch process and its modifications. The process offers almost unlimited possibilities for the manufacture of synthetic aliphatic chemicals and their derivatives, and either through aromatization, or in conjunction with coal hydrogenation, makes possible the synthesis of almost any organic compound from the commonest materials. Many well-known chemicals now in very extensive use can be made at a cost which would not give annoyance to an economist. It is claimed [5] that lubricating oils can be made by the catalytic reaction of carbon monoxide with a large excess of hydrogen between 482° and 697° F under 300 to 750 p.s.i. in a hydrocarbon medium (*e.g.*, anthracene oil) that remains liquid under the reaction conditions, and in which a catalyst (ZnO, MgO, and Fe) is suspended.

Lubricating oils are generally produced by polymerization of lower olefins, alkylation of aromatics, or condensation of aromatics with long-chain olefins. Such oils were used during the war with satisfactory results, though perhaps the claims made for them were a little emphasized.

I take the view that if we are to obtain a composite picture of petroleum we must consider every aspect of it. Whilst coal and oil shale may not provide us with lubricants to suit our immediate needs, they must be considered as potential raw materials in the field of synthesis. W. H. Cadman [6] recently reminded us that the enormous oil-shale deposits of the world form a potential raw material for the production of oil. Scotland alone produced 1·3 million tons of oil shale in 1946. The shale yields an average of 22 gal of oil per ton. The oil is particularly suitable for diesel oil, the yield being as high as 50 per cent by volume. Away back in 1913, when considerable thought was being given to fuel for the Navy, Winston Churchill estimated a probable annual output of 400,000 to 500,000 tons of fuel oil from Scottish oil shale for 150 years to come, if necessary. The published [7] output in 1913 was 250,000 tons. The oil shale in Sweden, in addition to giving oil, contains large quantities of uranium. It is estimated [8] that the shale may contain as much as 50,000 tons of uranium. It has been stated that 8 lb of uranium contain as much potential power as 6300 tons of fuel oil.

The insatiable demand for oil encouraged Congress to pass a Bill in 1944 authorizing the expenditure of $30 million over a period of five years for research on synthetic liquid fuels. In addition, many American oil companies are spending vast sums of money on similar projects.

Theory of Lubrication.

The theory of lubrication in some of its aspects forms a useful link between the established practices and future development. So it is interesting to note that Faraday mentioned the peculiar friction observed when a platinum rod is rubbed on a platinum plate which has been

thoroughly cleaned by making it the cathode in electrolysis, or by heating it in sulphuric acid. He claimed that friction tests made with clean surfaces gave fascinating results. Miss Agnes Pockels,[9] in 1891, made the very important discovery that very small amounts of oil on the surface of water have no appreciable effect on surface tension, but that the surface tension begins to decrease suddenly when the amount of oil per unit area is increased beyond a certain sharp limit. Rayleigh,[10] in 1899, repeated the experiments and emphasized the importance of the phenomenon. Hardy's [11] still more careful experiments have revealed in even greater measure the value of the Pockels law.

From these various experiments it appeared that *S* (Fig. 4) corresponds

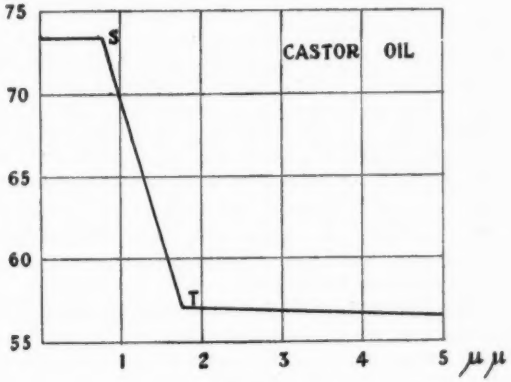

FIG. 4.

to a layer one molecule thick, and *T* to a double layer of molecules. Devaux [12] considered that the primary film is always a single layer of molecules, but he seems to doubt whether the point *T* does really relate to a double layer of molecules. He was inclined to the view that *T* represents a condition when the molecules are packed as closely as possible.

Then Langmuir [13] brightened the arena by the new conception of molecular orientation and " water-soluble " groups.

Rayleigh [14] turned his attention to the well-known fact that a few drops of water wetting the parts in contact will prevent a cup of tea from slipping about in a saucer. Hardy [15] expanded the investigation to the use of a glass carriage with a hemispherical base which was made to slide over a glass plate. A horizontal pull of 42 g was required to cause movement when the surface was covered by a film of oil. The superimposition of a film of water decreased the lubrication, the threshold value of the force rising to 126 g. The effect was the same when the water layer was a film deposited by the breath as it was when the plate was completely flooded, the force needed to bring about slipping being the least when the layer of oil was of insensible thickness. Therefore, in Rayleigh's own words, " friction is greater with a large dose than with a minute quantity of the same oil, and this is hard to explain."

Hardy started his investigations with this paradoxical phenomenon.

Both Hardy [16] and Langmuir [17] showed that the deposition of monomolecular films of materials, such as long-chain fatty acids, on metal and glass resulted in the lowering of static friction. Similar effects are obtained in the case of sliding friction, although, due to wear and tear of the film during sliding, considerably more film material may be required to maintain a low coefficient of friction. Hardy stressed the importance of this first adsorbed film and suggested that static friction is due entirely to the molecular interaction between this primary film on each surface, much in the same way as condensed films form on water. Beare and Bowden,[18] in 1935, confirmed the observation that the primary film is not sufficient in the case of kinetic friction.

As Hardy confined his attention almost solely to static friction, which is when motion is first apparent, Bowden decided to study kinetic friction. Bowden and Hughes [19] made the important statement that if a lubricant is used it is not added to the metal directly, but is superimposed on the film of contaminant. In support of this they found that the coefficient of friction between outgassed metals was more than twenty times as great as that observed with metals cleaned in the ordinary way. It is probable that the oxide layer reduces friction between unlubricated metals by weakening the metallic junctions between the surfaces. Unless the oxide film is very great it is not able to prevent the surface irregularities from breaking through. It is fortunate for engineering practice that metal surfaces are usually dirty.

The work of Bowden, and particularly his well-known stick-slip theory, has attracted much attention. One important development is the transition temperature from steady to unsteady movement, which has been emphasized by Frewing,[20] or that temperature at which the orientated layer becomes disordered.

Bristow [21] designed an apparatus to enable him to study the subject in his own way. He came to the conclusion that friction is not quite as Bowden had suggested. In fact, he went further and expressed the belief that stick-slip is due to an instrumental phenomenon. In other words, it is a function of velocity. Barwell and Milne told our Institute in January of this year that when using the Bristow apparatus, to make metals slide over each other in a lubricated condition, the composition and the surface structure of the metals must be considered with the lubricant in assessing the coefficient of friction.

All this work on theoretical considerations has brought into great prominence the effects of many organic compounds other than hydrocarbons. It must be stressed, however, that such compounds are really of interest under boundary conditions, and have no commensurate value in fluid-film lubrication, which is when the viscosity of the fluid determines the friction.

Hydrodynamic lubrication cannot occur when surfaces are too close together, as is often found in starting. Frequently it is difficult to decide whether or not to provide for boundary lubrication.

The advantages of aliphatic acids, and the presence of a hydroxyl group in static friction at atmospheric temperature, and their orientation, have been well illustrated. Above a certain temperature, called the

"transition temperature," attraction and orientation are stated to cease entirely.

Docosane	$C_{22}H_{46}$	43° C
Lauryl alcohol	$C_{12}H_{25}\cdot OH$	23
Octadecanol	$C_{18}H_{37}\cdot OH$	59
Stearic acid	$C_{17}H_{35}\cdot COOH$	69
Copper laurate	$Cu(C_{12}H_{23}O_2)_2$	110
Sodium stearate	$NaC_{18}H_{35}O_2$	290

These figures may be true only for some surfaces and quite untrue for other surfaces. Lauric acid, for example, will give good boundary results on copper up to 100° C, whereas on platinum it ceases at 43° C, the suggested reason being that it forms a soap on copper and not on platinum.

Transition temperatures may be modified by velocity. With ethyl palmitate at high velocities the kinetic friction decreases with increase of temperature, whereas at low velocities the kinetic friction increases.

Less than 1 per cent of oleic acid produces the minimum friction in static friction, but in kinetic friction there is a continuous reduction by increasing additions of oleic acid to mineral oil.[22] The effect is considerable up to 5 per cent, but above 5 per cent the effect is less marked.

The advantages of oiliness addition agents are now beyond doubt, provided always that they are scientifically chosen.

Chemical Additives.

Since the introduction of the hypoid-gear, extreme-pressure conditions have had to be cared for by other additives. The organic compounds which have stood the test of time so far have contained sulphur, chlorine, and phosphorus, either alone or together. They do not all function in the same way. Tricresyl phosphate is believed to be a polishing agent, whereas some sulphur compounds produce a protective film. The activity of the sulphur is all-important. Insufficient activity fails to produce the requisite film, whereas over-activity results in an attack of the metal surface. Probably the two best-known compounds are dibenzyl disulphide, $C_6H_5\cdot CH_2\cdot S\cdot S\cdot CH_2\cdot C_6H_5$, and di-(3-carbomethoxy-4-hydroxyphenyl)thioether,[23] although, of course, others have been used. A vast array has been suggested, some of which have found special applications.

The inevitable pressure of progress in the development of the internal-combustion engine has brought forth other imaginative creations to reduce ring-sticking, lacquer, and bearing corrosion, all of which are lumped together under the designation of heavy-duty oils. The present tendency is towards metallic compounds of thiophosphates.

Now that higher sulphur content fuel oils are on the increase it is certain that much more efficient additives will have to be provided.

With all the multiplication of efficiency methods in engineering comes a continuous demand for additives to meet the exceptional conditions imposed by high or low temperature, higher or lower speeds, higher pressures, and greater aeration.

Greater aeration during the war produced a rich field for romance. Out of the foaming troubles in aero engines sprang an activity in organo-silicon chemistry. Certain silicon compounds have the property of reducing foaming when present in minute quantities. Now they are being studied

because of other interesting properties. Silicone oils are noted for their very small change of viscosity with temperature, which makes them more suitable as lubricants and hydraulic fluids under a wider range of temperature than the hydrocarbon oils. Their low pour point enables them to be used at the freezing point of carbon dioxide. Their stability at high temperature has given the idea that they can be used as lubricants at high temperatures. Possibly the idea has been over-stressed in ignorance of their boiling points. Nevertheless, their stability gives them a very wide range of application. The silicon compounds which have been synthesized, however, are not universal lubricants.

The silicanes [24] exist from mobile fluids of low boiling point to solids with a high melting point.

	B.p.	M.p.
$(CH_3)_4Si$	26·5° C	
$(CH_3)_3Si$ (n-$C_{14}H_{29}$)	300	
$(C_6H_5)_4Si$	428	233° C
CH_3SiH_3	−57	−157
(iso-$C_5H_{11})_3SiH$	245	
$(C_6H_5)_3SiH$	—	202

The war was also responsible for an unexpected expansion of organic fluorides. Some of these compounds display an inertness comparable only with that of the inert gases. Hydrocarbons have been fluorinated to produce perfluoro-lubricating oils.[25] The fluorocarbons are unaffected by strong acids and alkalis, are non-inflammable and stable in air, and undergo decomposition only at a red heat. Unfortunately, however, they have a comparatively low boiling point, and have a high viscosity change with temperature. These disadvantages need not create depression, as the chemistry of fluorine compounds has advanced sufficiently to show the way to the production of a liberal array of compounds.

It has been stated that lubrication is "going chemical." Certainly we are on the road to this consummation—even if the road is long. To meet the broadened uses of hydrocarbon oils, which often lack the necessary flexibility, enhanced qualities have been imparted by chemical compounds under the general designations of pour point depressants, viscosity index improvers, autoxidants, corrosion arresters, detergents, film strength improvers, etc. With these weapons, lubrication has of necessity been subjected to a revaluation. This by-road of science has led past the delight of the mere process of discovery into the broad highway of industry and war. There is now a realistic movement to synthesize chemical compounds which can withstand the terrific ordeals to which lubricants are now subjected. The primary task is to produce something, and the second is to bring it into the price orbit. In the additive field we are still able to meet price demands, for how long nobody knows, because as the thrust on additives grows more complex, more expensive compounds become necessary. Synthetic lubricants, however, cannot at present compete in price with petroleum, although on an overall cost basis they may be cheaper for specific purposes.

The incentive to synthesize lubricants arose out of aircraft development and the conditions under which aircraft operate. Very high and very low temperatures are encountered in a very short space of time. Not long ago

it was sufficient to think of a temperature range of −40° to 250° F. To-day the range is −70° to above 300° F.

To meet such phenomenal demands, the chemist has turned his attention to synthetic organic compounds which have a very low pour point and very high viscosity index, and of course high stability. Most of the published references to these compounds have appeared since 1946, although much research was obviously conducted in the immediate preceding years. The polyalkylene glycols and their derivatives are of particular interest for hydraulic fluids, rubber lubrication, and claims are even made for them in various mechanical equipment. Among the mono-esters may be mentioned *n*-octyl adipate, *iso*-octyl sebacate and esters of mixed C–7 acids and trimethylol-ethane. These have been used alone, or blended with petroleum. The mono-esters appear to have been superseded by diesters made from dibasic straight-chain aliphatic acids.

A non-spreading lubricant for jewel-bearing instruments has been made of :—

Benzyl phenylundecanoate	60·0%
Diethylene glycol dicaproate	39·4
Dodecylpiperidine stearate	0·4
p-tert.-Butylcatechol	0·2

Special attention has also been given to grease manufacture, as the following formula will show :—

Di-2-ethylhexyl sebacate	34·8%
Di-2-ethylhexyl adipate	52
Lithium stearate	12
Polybutene	1
4-*tert.*-Butyl-2-phenylphenol	0·2

It is thus becoming more and more apparent that the differences between pure and applied science are becoming partially obliterated, and that results are not obtained by rubbing a lamp, but by a mechanism of some kind. Whilst we may live with the memory of the past, it is on the needs of the future that we must concentrate.

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Vote of Thanks.

Mr C. A. P. Southwell : The pleasant duty has fallen to me of proposing a hearty vote of thanks to our President for his address this evening. I should like also to take the opportunity to say again how much we owe to him for the work he has given to our Institute during his Presidential year (hear, hear); I say that both on behalf of Council and of all members of the Institute.

It is quite obvious that he has given a considerable amount of thought to his address. It is not customary to discuss a presidential address or to put questions in regard to it; but we are given the opportunity to read it in the *Journal* at a later date and to use it as food for thought in connexion with any further deliberations on the subjects discussed.

In Mr Evans we have had a President during the past year of great dignity, extreme courtesy, and a kindly humour. In fact, he has provided those lubricating qualities to our Council's deliberations which are so necessary to the success of this Institute.

I invite you all to accord a hearty vote of thanks to our President in the appropriate manner.

(The vote of thanks was accorded with enthusiasm, and the President briefly responded.)